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# Preliminary investigation of clay soil stabilization by electro-osmosis.

Christensen, Wayne J.; Christensen, Wayne J.

Rensselaer Polytechnic Institute

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PRELIMINARY INVESTIGATION OF  
CLAY SOIL STABILIZATION  
BY ELECTRO-OSMOSIS

WAYNE J. CHRISTENSEN

Thesis  
C45

Thesis  
C45

Postgraduate School.  
U. S. Naval Academy,  
Annapolis, Md.









PRELIMINARY INVESTIGATION  
OF  
CLAY SOIL STABILIZATION BY ELECTRO-OSMOSIS

Wayne J. Christensen  
Lieutenant, CEC, USN

Presented as partial fulfillment of the  
requirements for the degree of  
Master of Civil Engineering  
Rensselaer Polytechnic Institute  
Troy, New York

June 1948



Thesis  
C45

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## ACKNOWLEDGMENT

The author wishes to thank Professors E. J. Kilcawley and S. V. Best for their continued guidance during this work. It is also desired to express appreciation for the able assistance of Lt. (jg) W. B. Stephenson (CEC), USN, who will carry on the work.



LETTER OF TRANSMITTAL



159 Ninth Street  
Troy, New York  
June 7, 1948

Faculty  
Civil Engineering Department  
Rensselaer Polytechnic Institute  
Troy, New York

Gentlemen;

As partial fulfillment of the requirements for the degree of Master of Civil Engineering, I have the honor of submitting this thesis for your approval. It is hoped that the results of this investigation can be used to advantage by other investigators in the near future.

I should like to express my appreciation for the knowledge and guidance you have bestowed upon me during my stay at Rensselaer.

Sincerely yours,

Wayne J. Christensen  
Lieut., CEC, USN





## INTRODUCTION



## INTRODUCTION

There have been many significant advances during recent years, in our understanding of the performance of soils used for engineering purposes. There remain, however, many variables which complicate the design and construction of foundations for structures. These variables are usually unpredictable to some degree and may greatly increase the total cost of structures. These variables are also the cause of many failures during construction or after completion of the structures. The majority of these failures have been due to unexpected settlement, swelling, lateral movements or other unexpected performances of the soil.

It is possible, using proper design, to construct modern structures on nearly any type of soil. Such construction may, however, be unfeasable due to excess cost of foundations on soil with low bearing capacity. It is therefore necessary to make an economic study to find if construction should be undertaken at a certain site instead of a more expensive site with a more desirable foundation material.

Past experience has shown plastic clay and silt soils to be especially troublesome and unpredictable foundation materials. Under many circumstances, construction on





this type of soil is necessary. Since this is usually a very expensive proposition, it would be desirable to decrease this expense by some method. The answer probably lies in some form of soil stabilization which would increase its bearing capacity.

There are several methods of increasing the bearing power of soils. A well known patented process for chemical soil stabilization is the Joosten process. It consists of injecting a solution of silicate of soda through injection pipes as the pipes are being driven. A second chemical, calcium chloride, is injected as the pipes are being removed. The calcium chloride removes water from the sodium silicate solution forming a silicic gel which fills the voids of the soil and binds the particles together. This method has been found effective in cohesionless soils only.

A grouting process such as an injection of fluid cement grout into the soil mass is also used. This grout, if injected in successive applications, cements the soil particles together and forms a solidified material similar to weak concrete. This method is also effective on cohesionless soils only.

The Francois cementation process is similar to the



grouting process with pressures up to 3000 pounds per square inch being used for injection. The voids are filled with cement grout which sets, forming a mass of concrete. This method is effective on sands and gravels.

Another fairly well known process is freezing. This consists of placing pipes into the soil for the circulation of freezing brine. This method can be used on all types of soil but the application is slow and expensive. This process offers only a temporary solution to the problem.

During the past few years, an entirely new method of stabilization has presented itself. This process is by electro-chemical treatment and electrical drainage. Recent research has proved that a clay soil can be drained effectively by means of electro-osmosis. There is also an indication of stabilization by base ion exchange but the extent of this type of stabilization has not been determined to date.

This method of stabilization appears to be the only practical way to improve the bearing capacity of clayey soils. The method has already proved its worth in several practical instances. It is not known however, if the method produces permanent stabilization.





## ABSTRACT

This thesis is only one of a series of investigations to be conducted on this subject at Rensselaer Polytechnic Institute. The ultimate goal of these investigations being a thorough knowledge of the electro-chemical nature of clay soils and the exact nature of the electro-osmotic phenomenon. With this knowledge, it would probably be possible to analyze a certain soil and predict with some degree of accuracy, the effect of the electrical treatment on the soil.

A brief generalization of the theory of electro-chemical stabilization and electro-osmosis is presented. This theory has been proved by recent investigations to be sound. A summary of some of these investigations is given.

The purpose of this investigation is to determine if possible, the effect of this method on some of the physical and mechanical properties of a given soil. It was desired to control the amount of current passing through the soil mass. This was impossible, however, since the voltage available was not high enough for complete satisfaction.

The effect of distance from the electrodes was



studied to determine the radius of influence of this method of treatment on soil properties and drainage.

Samples of soil, before and after treatment, have been preserved for future investigators to use in determining the chemical changes and changes in crystalline structure which have probably occurred.





## THEORY

The theory of clay stabilization by the electro-chemical method has arisen from basic knowledge and from theories of the electro-chemical nature and structure of clay minerals.

At the present time there are several ways of classifying clay. One method is by particle size. As defined by Baver (15); "Clays are disperse systems of the colloidal products of weathering in which secondary mineral particals of smaller dimensions than 2 microns predominate". These minute mineral particles are derived mostly from the decomposition of feldspars and similar silicates. As such, they are complex hydrous aluminum silicates. They are crystalline in nature and have been found to be flake-like in structure.

The most important clay minerals are as follows:

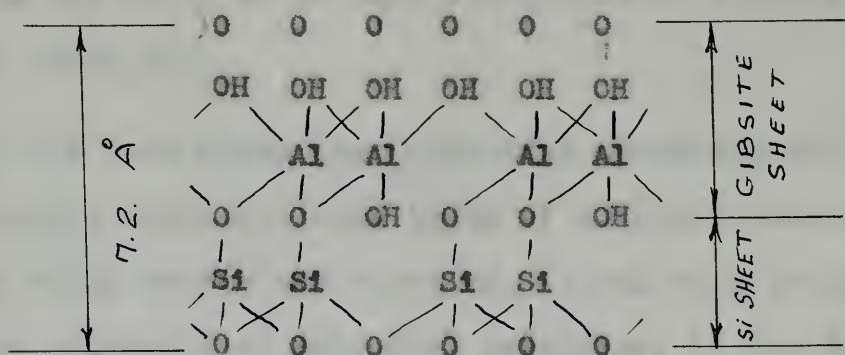
Kaolinite	-	$\text{Al}_2\text{O}_3$	·	$2\text{SiO}_2$	·	$2\text{H}_2\text{O}$
Anauxite	-	$\text{Al}_2\text{O}_3$	·	$3\text{SiO}_2$	·	$2\text{H}_2\text{O}$
Halloysite	-	$\text{Al}_2\text{O}_3$	·	$2\text{SiO}_2$	·	$x\text{H}_2\text{O}$
Beidellite	-	$\text{Al}_2\text{O}_3$	·	$3\text{SiO}_2$	·	$x\text{H}_2\text{O}$
Montmorillonite	-	$\text{Al}_2\text{O}_3$	·	$3\text{SiO}_2$	·	$\text{H}_2\text{O}$

The structure of feldspars, from which clay is derived, are built up of tetrahedral groups of O atoms around Si or



Al atoms. These groups are arranged so that each O atom is common to two tetrahedral groups. When a Si atom is replaced by an aluminum atom, the charges become unbalanced and a negatively charged network results. This forms a three dimensional anion whose charge must be balanced by some cation. This reaction possibly happens in the decomposition of feldspars to form clay minerals.

Only two types of clay minerals will be discussed here. They are Kaolinite and Montmorillonite. The Kaolinite crystal has a fixed 1:1 lattice structure with a low base exchange capacity and as a result, it adsorbs a comparatively small amount of water and therefore does not exhibit much swelling. The kaolinite crystal lattice is made up of a gibbsite octahedral sheet and a silica tetrahedral sheet as indicated below.

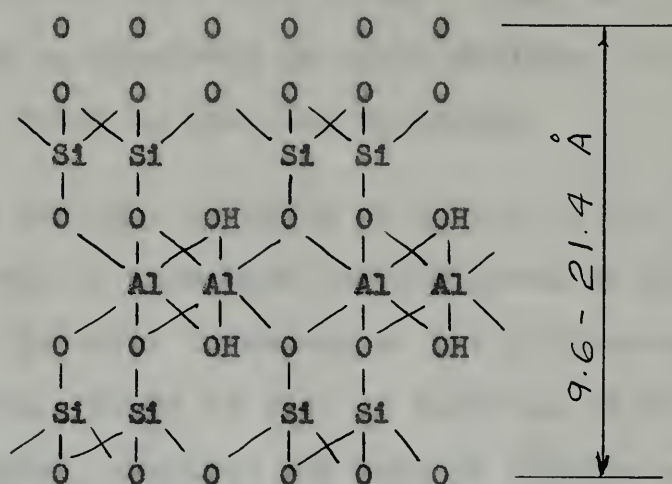


Montmorillonite on the other hand, has an expanding, accordian-like structure composed of a 2:1 crystal lattice.





This mineral has a high base exchange capacity. It therefore adsorbs a great quantity of water and exhibits great swelling capacity. The montmorillonite sheet is capable of expanding from 9.6 to 21.4 Angstrom units. This means that a partical is capable of doubling in size with the adsorption of water under optimum conditions. The montmorillonite lattice structure is shown below.



All the other known clay minerals have properties between these two.

It has been found that colloidal particals are electrically charged. Some types of colloids are positively charged while others are negative. Since clay soils are composed primarily of colloidal particles, it can be concluded that they will have free positive and negative charges. In the case of podsoils, the charges are predominantly negative where as the charges on laterites are mostly positive. These unbalanced charges cause a state



of unequilibrium which must be balanced by adsorbed ions of opposite charge. Since podsoils predominate in temperate climates, they alone are considered herein. It is necessary to balance the excess negative charge of the particles by positively charged ions called cations. These cations are bound to the surfaces of the clay particles and between the sheets of the lattice structure. The cations are not held very firmly. They are, therefore, mobile and can be displaced by other cations. This exchange of cations is known as base ion exchange.

The base exchange capacity of a clay is the amount of ions that can be exchanged per 100 grams of soil. This exchange capacity increases as the silica-sesquioxide ratio increases. There is also an increase in the amount of adsorbed water, swelling and heat of wetting as the exchange capacity increases.

It has been shown that the amount of water taken up by the soil colloids varies with the kind of adsorbed cations. Therefore, the amount of swelling will depend upon the adsorbed cations.

In general, the higher valent adsorbed cations produce greater stability of the soil particles. The exception to this rule is the H ion whose exact action is not known. The larger the total exchange capacity,





the greater the amount of water which can be adsorbed. To explain this, it is assumed that the adsorbed cations are surrounded by an atmosphere of adsorbed water molecules. This water takes up space and is the cause of the swelling which occurs in the clay. The stability of these soils can be improved by decreasing the amount of adsorbed water and this can be done by decreasing the amount of adsorbed cations. By using trivalent ions, fewer are required to satisfy the charges on the clay particles. This results in a smaller quantity of adsorbed water and consequently less swelling. It is on this principle that the theory of stabilization of clay by electro-osmosis is based. The adsorbed ions being replaced by ions which are more beneficial. By using an anode of tri-valent metal such as aluminum, the desired action occurs. The aluminum ions leave the electrode by action of the electric current and replace the lower valent ions. These replaced ions migrate to the cathode. The result of this action is a stabilization of the clay mass.



## PREVIOUS WORK

The previous work on soil stabilization by electro-osmosis is very limited since it is an entirely new method. As far as is known to the author, the first experiments conducted using this method, began in Germany about 1935 under the direction of Drs. Leo Casagrande and L. Erlenbach.

The earliest work done by Dr. Casagrande consisted of model experiments on blocks of clay and testing the effect of the treatment on stability. The electrodes consisted of an aluminum anode and a copper cathode. He found that the moisture content could be decreased from 30 to 40 percent, that the angle of internal friction increased, and that the soil mass became very hard after treatment.

Dr. Kurd Endell did some experimentation on this method at the laboratories of the Technical Academy of Structural Technology, Berlin. He used a similar electrode setup on a sodium clay having strong tendencies to swell and slide. The results of his tests showed marked increase in resistance to penetration and water erosion. The soil immediately around the anode had lost its high swelling properties even when submerged in water.





During the following year, 1936, Dr. Erlenbach made some model tests of the electro-chemical method on floating pile foundations. He found that the bearing power of friction piles could be increased about five times after only five hours of treatment.

Dr. Casagrande followed these tests in 1937 with similar tests on a natural scale. Due to the lack of copper, aluminum sheathed piles were used as electrodes and consolidation occurred at both electrodes. The tests were carried on in a Chiemsee clay layer. The soil being homogeneous to a depth of sixty meters. The surface of the soil was covered with stagnant water which proved to have no disturbing influence on the process. An examination of the aluminum sheathing after treatment showed that it had been uniformly consumed throughout the length of the pile on all exposed surfaces. The power consumed varied from 260 KWA to 2000 KWA. The conclusions reached were that up to a certain limit, a relatively small current consumption greatly increased the bearing capacity of the piles and above this limit, the bearing capacity decreases.

The following is a summary of a report on large scale tests and practical applications of electro-osmosis by Dr. Casagrande.



In making a railway cut near Salzgitter, Germany, the construction of slopes was impossible even in dry weather due to the instability of the soil, a loess-loam deposit. Well electrodes 7.5 m. long were spaced at 10 meters along the cut. Rod electrodes consisting of 1 cm. diameter gas pipe were used as anodes and placed between the wells. Water was driven by the current to the well electrodes for removal by pumping. The current was 19 amperes per well at 180 volts pressure. It was found that the amount of water removed was 150 times the amount collected without the action of the current. After a brief period of osmosis, the soil supported adequately the weight of the excavator and slopes could easily be constructed to a slope even greater than that desired. It was found that an interruption of the current for a period of six hours or greater, resulted in a sloughing off of the wet material forming the slope in the vicinity of the shut off. If the current was resumed, this sloughing off ceased after a short period.

During the construction of a U-boat pen at Trenchjem, difficulties were encountered in taking out the excavation due to serious earth movements and uplift of the floor, even though protected by two rows of sheet piling. The proximity of the sea added to the dangers of these movements,





After reaching a depth of 8 meters, it became impossible to excavate further because the floor would rise up as fast as the excavation progressed. The soil was a clayey silt with seams of sand. The electro-osmosis treatment was applied using wells 29 meters long and 10 meters spacing for cathodes. A voltage of 40 was applied resulting in a current of 20 to 30 amps per well. As a result of this treatment, the slopes and floor could be excavated without further difficulty.

A tunnel was being constructed through massive rock in the Lerkendal Valley, near Trondhjem. It was necessary, however, to construct the tunnel through an extensive, deep deposit of clayey silt. This construction would have been extremely expensive if ordinary methods had been employed. The application of electro-osmosis was used with great success by using wells as cathodes spaced at 10 meters and rods between them as anodes. The electrodes were driven two feet below the elevation of the proposed cut. As a result of this treatment, construction continued satisfactorily. An attempt by the contractor to excavate beyond the influence of the current ended in failure.

Experiments were conducted on lime sludge deposits formed from industrial wastes at Wulfrath. The results are quoted as follows: (2)



1. With uneconomically high amounts of current, an extensive and almost unlimited amount of drying out may be attained.

2. Since the electrodes clog rapidly and therefore increase the resistance, they must be cleaned frequently or otherwise replaced by new ones.

3. The higher the moisture content, the better and quicker is the action of electro-osmosis. With a decreasing water content, the process of moisture removal is slowed down, approximately in direct ratio.

4. Reduction in moisture content of the order of 10 to 20 percent of the original value may be obtained without difficulty and with an economic current consumption.

5. After a prolonged treatment with electrical current, the moisture content in the neighborhood of both the electrodes is reduced.

A limited amount of information is available in an abstract of two Russian papers published by the academy of sciences of U.S.S.R. in 1941. These papers claimed that the cost of stabilizing clay by electro-chemical treatment was among the cheaper methods. The cost of treatment being 10 to 50 roubles as compared with 50 to 200 roubles for other methods. B. A. Rzhantzin





found that the density and bearing power was greatly increased by application of the method using an aluminum anode and a copper cathode. They found the best field results were obtained at 100 to 22 volts per meter with a current under 20 amperes per square meter. The best electrode spacing was between 0.5 and 1.0 meters. It was found that an addition of calcium chloride or sodium chloride was helpful in stabilizing clays of low base exchange capacity. This type of soil could not be stabilized by current alone.

D. I. Solntzen and B.S. Borkov, investigating the effect of electro-chemical treatment on frost heaving of clay soil, found that an addition of sodium chloride together with an electric current caused more than a tenfold decrease of frost heave but causes excessive swelling of the soil when wetted. The addition of 0.2% calcium chloride caused a decrease in frost heave, plasticity index and swelling.

Dr. Hans Winterkorn investigated the flow of water caused by the action of an electric current. He expressed the volume of liquid transported through a capillary in unit time as,  $V = \frac{\pi r^2 DE}{\eta 4 \pi} = \frac{r^2 D \phi E}{4 \eta}$  where;

V = volume of water transported in one capillary per unit of time.



$r$  = radius of the capillary

$D$  = Dielectric constant of water

$E$  = applied potential (volts/cm.)

$\phi$  = the interfacial potential

$\eta$  = viscosity of water

Converting this equation for engineering usage, an expression similar to the Darcy formula for flow under hydrostatic head was developed. This equation is as follows;  $V_p = nK_oE$  where,

$V_p$  = volume of liquid moved in a unit time through  
a unit cross section of a porous system

$n$  = porosity

$K_o$  = a material constant expressing the electric,  
dielectric and viscosity interrelationship  
at a solid-<sup>liquid</sup>~~solid~~ interphase.

This flow is not a function of individual pore size but rather of the porosity. This indicates that permeability is not a factor in electro-osmotic flow.





## REPORT





## APPARATUS

The following equipment was used:

- a. A low voltage power supply, 3300 watts at 110 volts pressure.
- b. A Weston D.C. Ammeter, 25 amp capacity.
- c. A Weston D.C. voltmeter, 150 volts capacity.
- d. A one ohm slide wire resistor.
- e. A resistor consisting of electric lamps in parallel.
- f. Test boxes, 4' by 6" by 12" inside dimensions.
- g. Standard liquid limit apparatus.
- h. Graduated cylinders, 1000 ml.
- i. Aluminum electrodes, .102 ga. annealed sheets.

The clay used in these experiments was a stiff blue clay obtained from the Bleau Brick Yard on Oil Mill Hill, a few miles north of Troy, New York. All experimentation was done in the soil mechanics laboratory, Troy Building, Rensselaer Polytechnic Institute.



## PROCEDURE

The clay used in these experiments was prepared by taking air dried pieces of clay and grinding them to a consistency from fine sand to powder. This ground up material was mixed with water in a steel drum. Enough water was added to bring the moisture content to some value above the liquid limit of the soil.

The wooden boxes were prepared to receive the clay mud by coating the inside surfaces with parafin. Holes were drilled in the bottom at the location of the electrodes to facilitate drainage. The electrodes were put into place and the clay mud, previously prepared, was poured in to the box around the electrodes.

A D.C. voltage was applied to the electrodes, records being kept of the resulting current and the amount of drainage from the cathode.

In all experiments, the treatment was continued until the soil mass dried out to such an extent that the increased resistivity lowered the current to so low a value that practically all action had ceased.

It was desired to determine the effect of the electrical treatment on the stability of the soil. To determine this, the changes in moisture content and Atterburg's limits were determined. In addition





to the actual changes in these constants, Their variation with respect to distance from the electrodes was studied. The purpose of this study being to determine if possible, the distance to which the treatment is effective.

The method of sampling for moisture content was; first to remove approximately  $1\frac{1}{2}$ " of material forming the top layer to avoid as much as possible the effect of evaporation from the surface. Next a piece of clay was dug out with a trowel. From this piece of clay, a sample was quickly removed to a weighing bottle and the moisture content determined.

Larger samples were dug out and allowed to become air dried. From these samples, Atterburg's limits were determined in the usual manner.





## EXPERIMENT 1

For this experiment, ten ga. aluminum sheets were used for electrodes. The sheets were cut six inches wide to extend completely across the box. Slots were cut in the bottom of the box to facilitate drainage at the electrodes. The electrodes were spaced 12 inches apart and the box was filled with clay mud.

The clay prior to treatment was well into the liquid range, having a moisture content of 54.3%. A voltage of 107 D.C. was applied across the electrodes. The resulting current of 1.0 amp indicated a surprisingly high electrical resistance in the wet clay mass.

The effect of the current was immediately evident. There was drying at the anode and an accumulation of water at the cathode. The water failed to drain off because the clay has packed around the electrodes. As a result, the water driven off came to the surface and soon the entire surface was flooded.

During the entire experiment, gas was coming off both electrodes. The gases were not analyzed, however, a flame test showed the gas coming off the cathode to be explosive. This gas was probably hydrogen, liberated by hydrolysis. The gas coming off the anode was flammable and had the odor of hydrogen sulfide.



After one hour and ten minutes of treatment, 100 ml. of water was siphoned off. The water was extremely turbid and immediately upon collection, the suspended solids flocculated and settled out leaving a clear liquid. This coagulation indicated the presence of an electrolyte. A test with pH indicator paper showed the liquor to have a pH of ten or greater. This shows that a strong alkali is formed and indicates that the OH ions formed in hydrolysis are combining with the cations displaced by the aluminum ions. The H ions, receiving electrons from the cathode go off as a gas.

The current increased to 1.2 amps during the first hour of treatment. The decrease in electrical resistance probably being due to an ionization in the soil mass caused by the current.

After a few hours of treatment, the area adjacent to the anode showed some tension cracks due to drying out. a groove was cut in the surface of the soil allowed the excess water at the cathode to flow to the anode. It was absorbed by the dryer soil at the anode and recirculated by the current. At this time, the current was decreasing. This decrease in current was probably due to the increased resistivity of the dryer soil.

A piece of copper tubing was passed through the clay





mass at the electrode, The top being level with the surface of the clay. This allowed the excess water to drain off for collection.

As the experiment continued, the clay mass continued to dry out and shrinkage cracks appeared across the box at both electrodes. These shrinkage cracks soon became quite extensive at frequent intervals across the box. The clay also shrunk away from the sides of the box.

After thirty hours of treatment, the current had decreased to 0.3 amps and process was stopped. At this time, the clay had become very hard, particularly at the anode. There had been 1213 ml. of water drained off the cathode. The moisture content had decreased to 28.2% at the anode, 29.8% between electrodes, and 30.3% at the cathode. This showed an average reduction in moisture content of 24.9%. The soil behind the electrodes was out of the influence of the current and remained in the liquid state.

Figure 1 is a graphical illustration showing the effect of time on the current and on electrical drainage.

The electrodes were removed after the completion of the experiment. The dry clay had adhered to the





# EXPERIMENT I

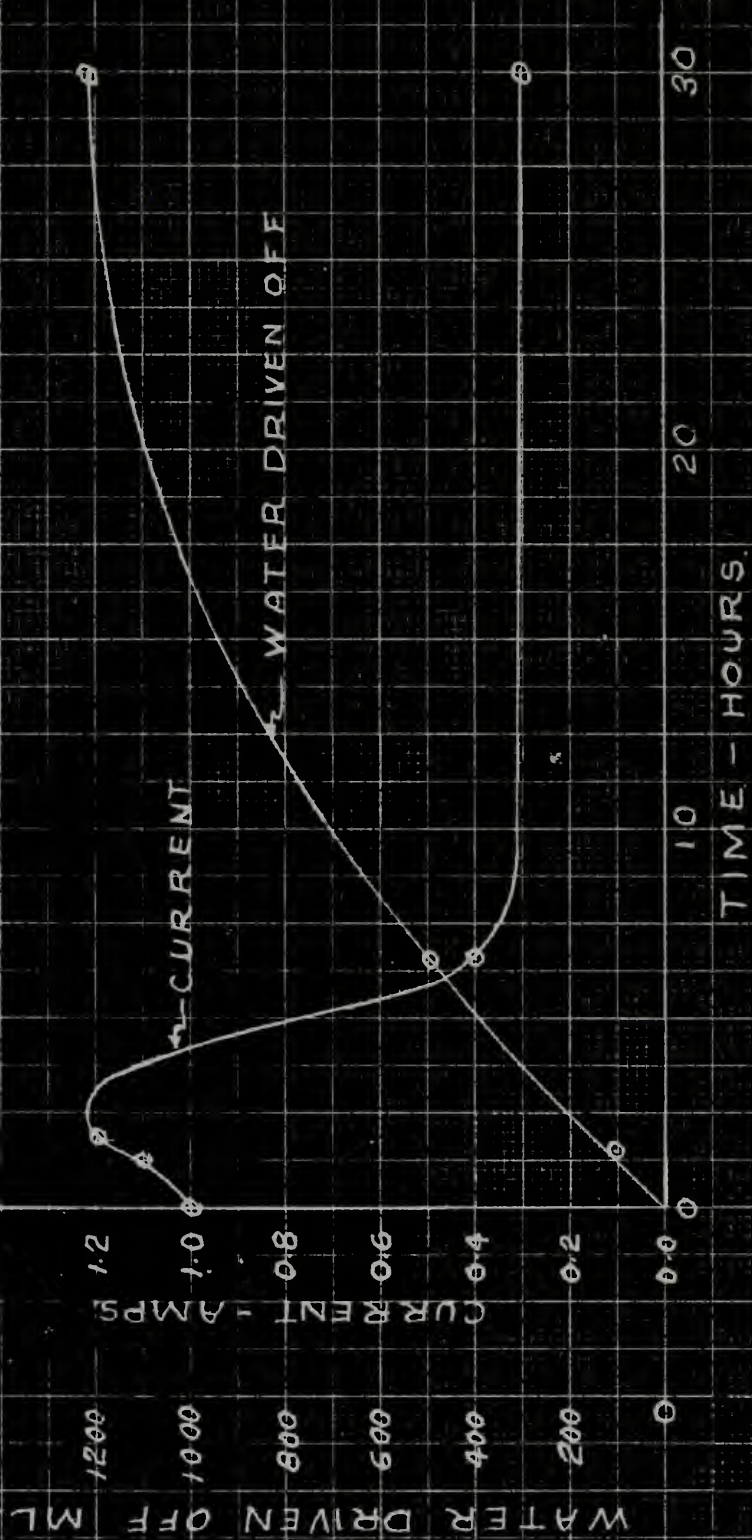


FIGURE 1





electrodes either cementation or interlock of the clay crystals and considerable force had to be exerted to extract them. Both electrodes showed marked pitting erosion on the inside faces. There was no reaction on the face out of the field of the current. In addition to the pitting, the anode was covered with a white deposit which previous investigators have identified as bauxite. The electrodes after treatment are shown in figure 2.

The liquid limit of the soil prior to treatment was 31.4%. This limit was increased to 41.5% at the anode and 47.6% at the cathode by the action of the current.

The original plastic limit was 21.4%. This limit was increased to 24.4% at the anode and 27.1% at the cathode. The plasticity index increased from 10.1% to 17.1% at the anode and 20.5% at the cathode.

A cube of soil approximately  $1\frac{1}{2}$  inches in dimension was cut from the soil immediately adjacent to the anode. This cube of soil was submerged in tap water and it maintained its original shape during six weeks of submergence. A similar cube of untreated soil fell apart completely in a few hours.





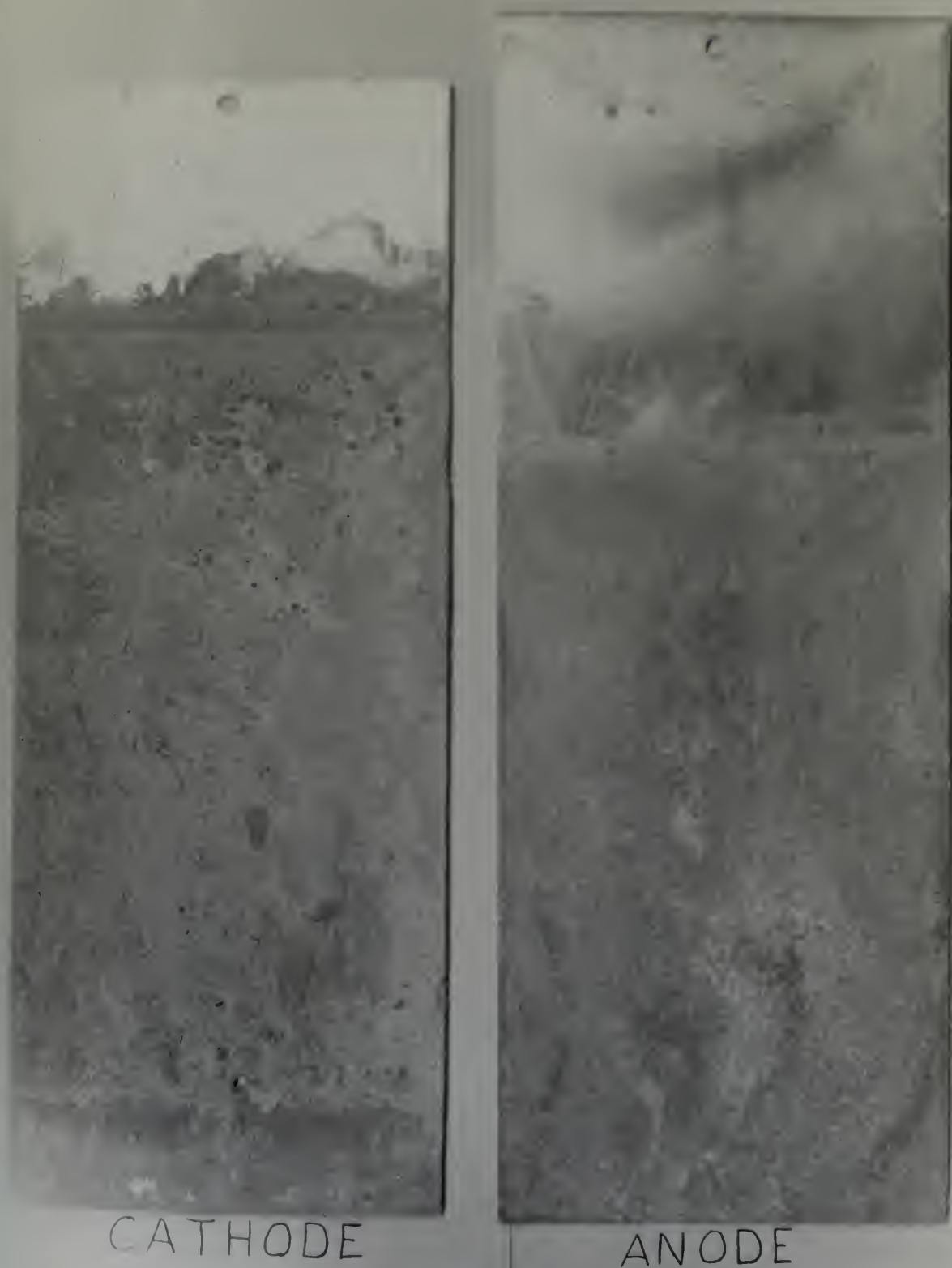


FIGURE 2



## EXPERIMENT 11

Using information gained from experiment 1, electrodes were fashioned from sheets identical to those previously used. The sheets were bent into cylinders and thoroughly perforated to give the effect of well points. The electrode spacing was again 12 inches. These electrodes permitted free drainage and proved to be very satisfactory.

The moisture content at the beginning of the experiment was 48.5%. The starting voltage was 110 with a current of 1.2 amps. This current increased slightly with time to a maximum value of 1.25 amps at one hour and thirty minutes. It then fell off rapidly as the soil dried out and the electrical resistance increased.

Water began dripping from the cathode immediately upon application of the current. This data is expressed graphically in figure 3. It should be especially noted that the amount of water driven off was nearly double the amount driven off in experiment 1 per ampere hour. This was probably due to the excellent drainage afforded by the well points.

The current had been going only a few minutes when radial tension cracks began showing at the anode. After one hour, concentric as well as radial cracks were becoming very pronounced at the anode. At this





# EXPERIMENT II

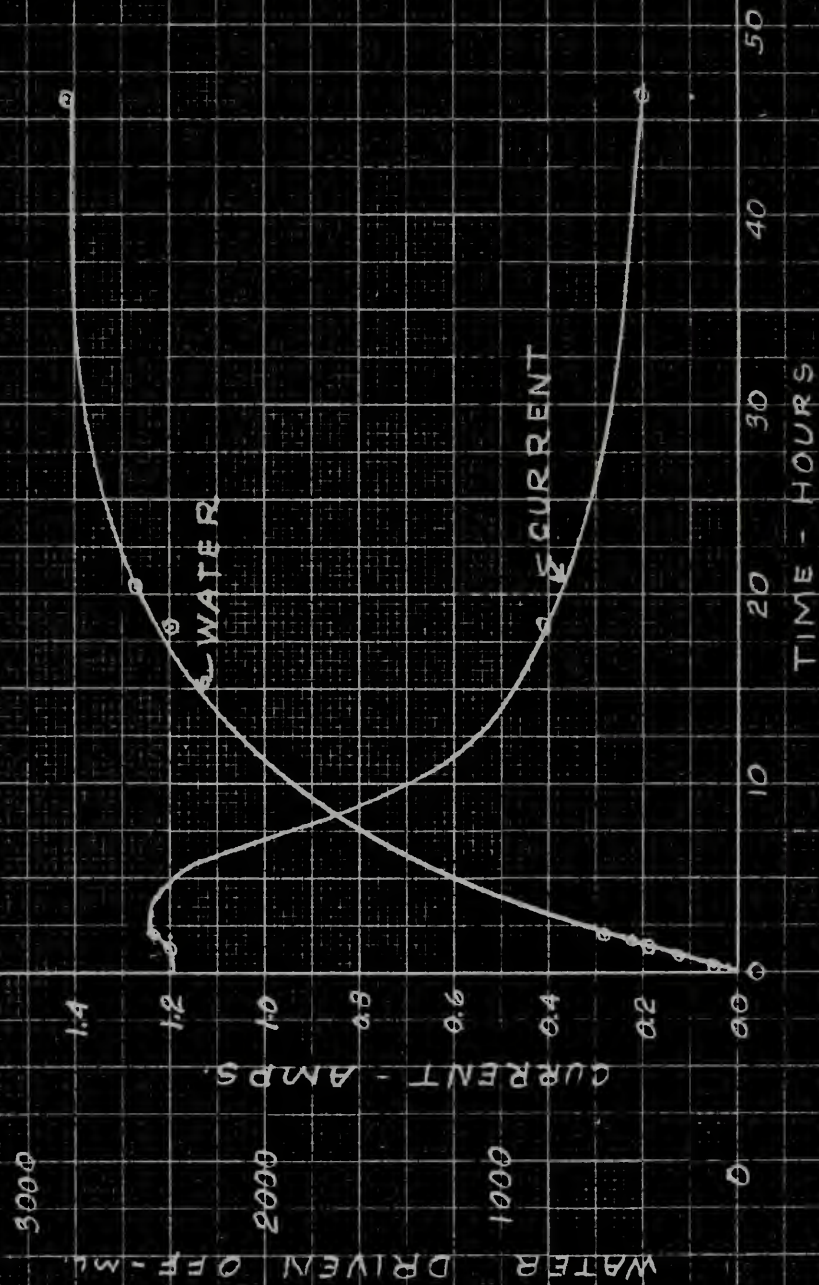


FIGURE 3





time similar cracking occurred at the cathode although they were not so large.

The water drained off had a pH greater than ten during the entire experiment. After eighteen hours of treatment, this water was analyzed qualitatively for base metals. The results showed nearly 100% calcium. a flame test revealed traces of sodium, potassium, and magnesium to be present. There was no aluminum or iron in the water. The absence of aluminum was very interesting, since the electrodes had been eaten away by the process. This is evidence that the aluminum ions were driven into the soil and liberated calcium by a base exchange of the adsorbed cations.

The current had decreased to 0.2 amps after 46 hours of treatment and the process was stopped.

The results of this experiment were very similar to the results of experiment 1 except that they were even more pronounced. The moisture content decreased from 48.5% to 22.1% at the anode, 26.2% between the electrodes and 30.0% at the cathode.

The change in plastic limit was the same as the change in plastic limit in experiment 1.



### EXPERIMENT 3

Aluminum well point electrodes, identical to those used in experiment 2, were used in this experiment. The electrode spacing was made forty inches and the box was filled with clay mud having a moisture content of 64.5%.

The starting voltage was 105 across the electrodes with a current of 0.35 amps. The soil was tested and found to have a pH near seven. This tends to prove that the presence of a strong alkali in the water driven off is not due to leaching of the soil but is derived from an electro-chemical change in the soil mass. Samples of the water driven off were taken at intervals to determine the amount of dissolved solids present. The results showed 1588 ppm dissolved solids after 27 hours 15 minutes of treatment, 1044 ppm after 3 hours 50 minutes, 678 ppm after 52 hours 15 minutes and 806 ppm after 96 hours. It is possible and probable that the ions least firmly bound are driven off first while those more firmly bound are driven off later. This can be determined only by a series of tests or chemical analyses of the water driven off.

The current climbed to a maximum value of 0.41 amps after 2 hours 50 minutes of treatment. At this time, the voltage was 108. The current then remained







# EXPERIMENT III

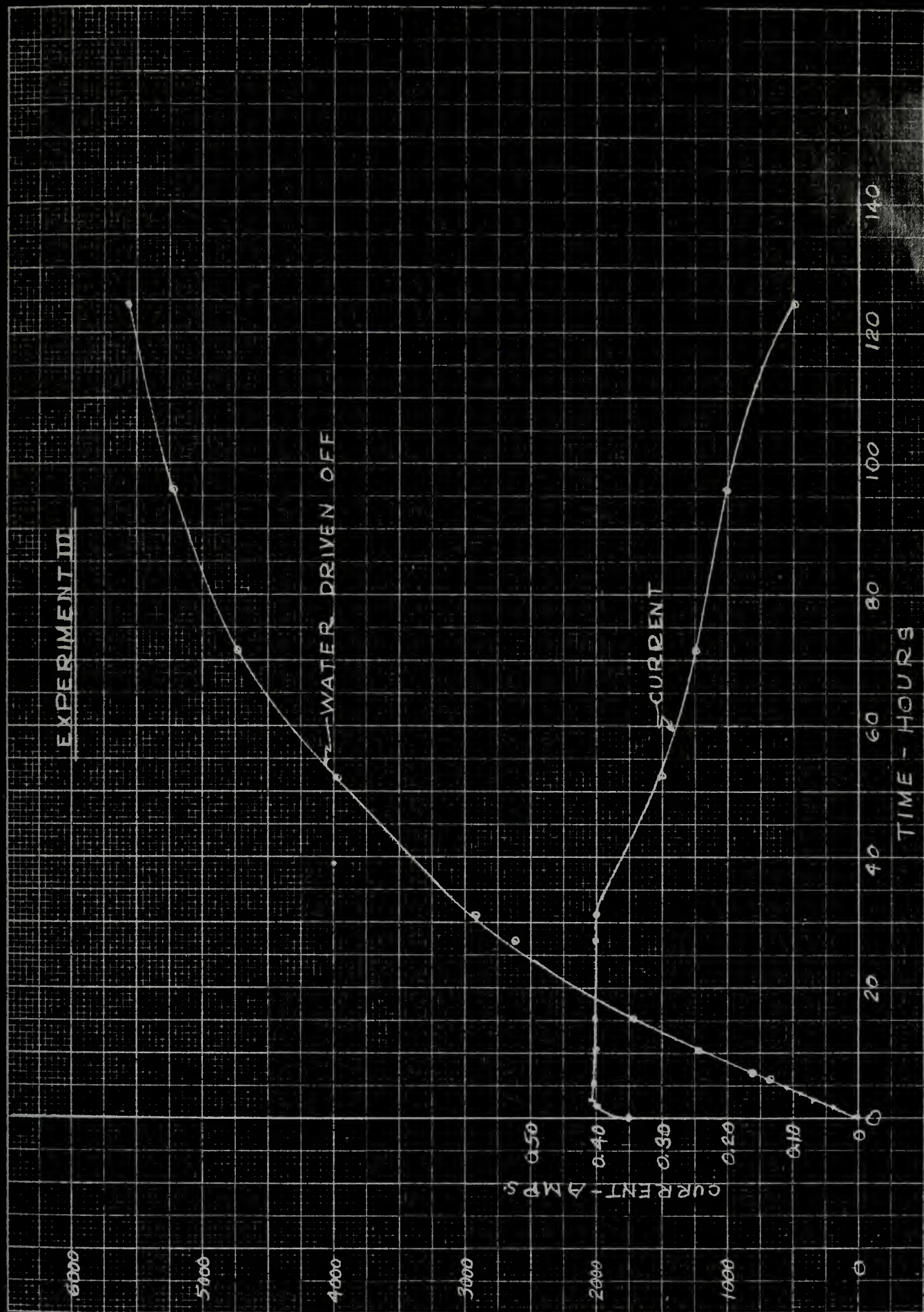
WATER DRIVEN OFF

CURRENT - AMPS

WATER - ML

TIME - HOURS

FIGURE 4





constant for approximately thirty hours as illustrated in figure 4. From this time on, there is a marked falling off of the current curve.

The water driven off was directly proportional to the ampere hours during the first part of the experiment. Figure 5 shows the curve of water driven off vs. amp hours to be a straight line during the first 6 ampere hours or 15 hours of time. After 15 hours, the curve fell off slowly. The slope of these curves would give the rate of flow if the current were held constant. since the slope of the curve for experiment 3 is greater than the slope of the curve for experiment 2, the amount of drainage per ampere hour is increased by the use of larger spacing. This increase could be the result of the lower current, indicating that better efficiency is attained by lower current.

During this experiment, records were kept of the settlement. The control points being at the anode, the cathode and between the electrodes. There was a gradual subsidence of the clay. The settlement being most pronounced at the cathode. This seemed to be very odd, since the greatest drying occurred at the anode.





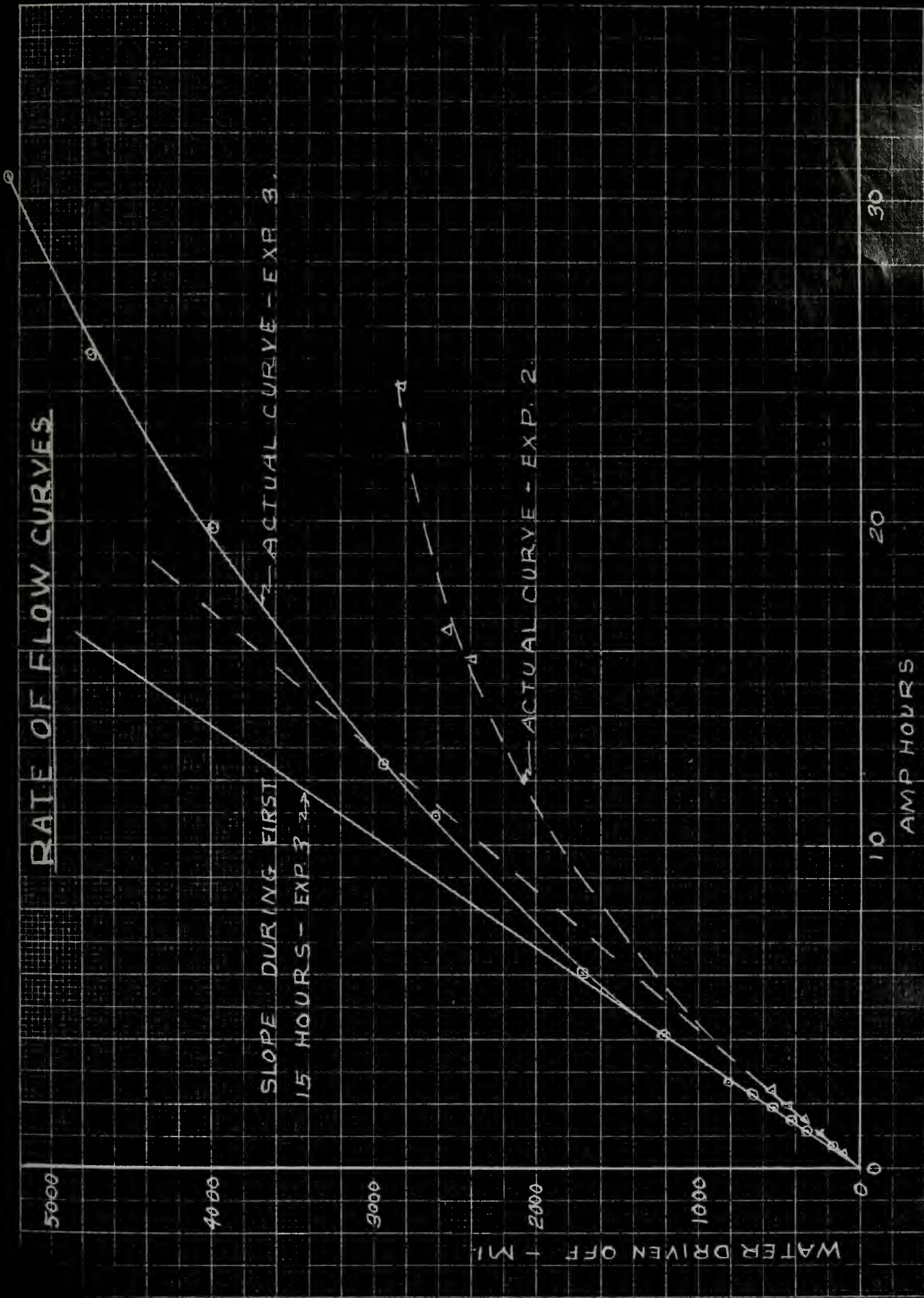


FIGURE 5





# EXPERIMENT III

## SETTLEMENT CURVES

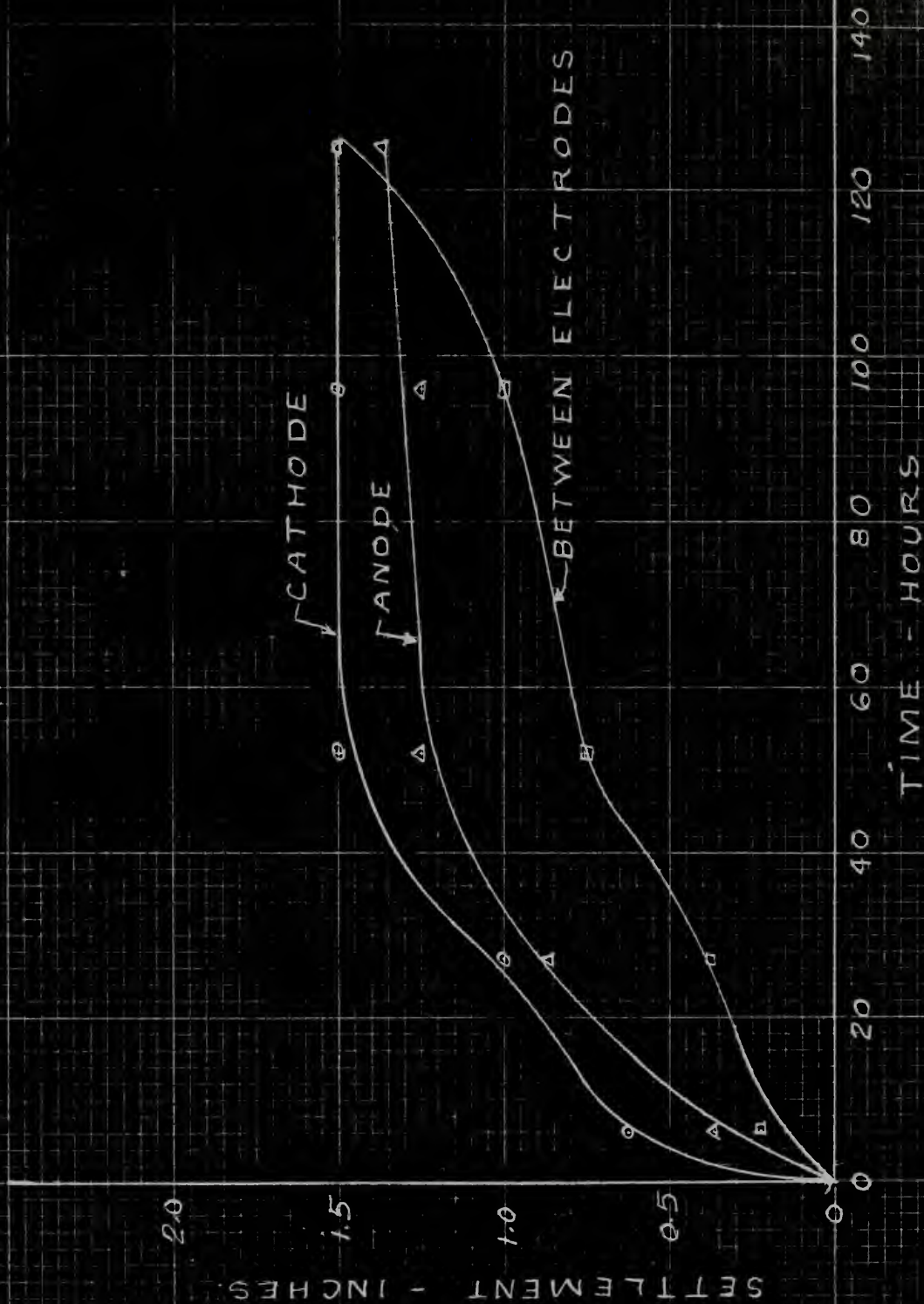


FIGURE 6



The slowest to settle was the area between the electrodes. This experiment indicates that settlement occurs at the electrodes first, then gradually works toward the center of the soil mass.

The greatest total settlement to occur was 1.75 inches at a point one foot from the anode. The author has no explanation for this phenomenon. This settlement expressed as a percentage of the original depth was about 18.4%, showing the volume of voids and voids ratio had been greatly reduced. Figure 6 gives settlement curves for the control points.

After 125 hours, the treatment was stopped. The moisture content of the entire soil mass had decreased considerably as shown in figure 7. The peculiar shape of the curve cannot be explained at this time.

The changes in liquid limit, plastic limit and plasticity index were very similar to the changes during the other experiments. The greatest change in these constants occurred at the cathode. Figure 8 shows the variation of these constants with distance from the electrodes.

An interesting feature of the treatment was that although the soil immediately around the cathode was fairly high in moisture content, it had lost much of







# EXPERIMENT III

ORIGINAL M.C. = 64.5%

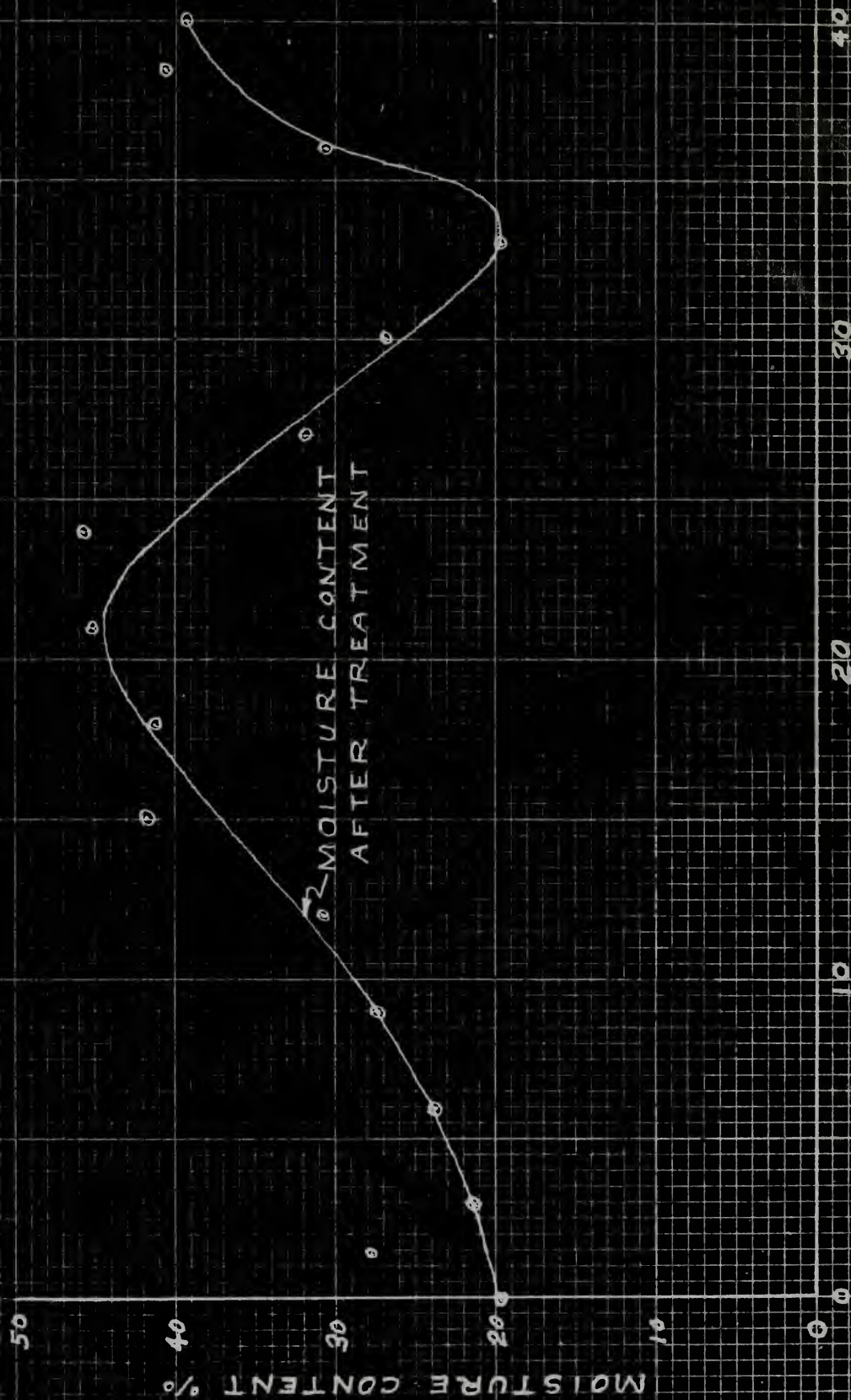


FIGURE 7



# EXPERIMENT III

ORIGINAL L.L. = 31.5%  
" P.L. = 21.4%  
" PI = 10.1%

ELECTRODE SPACING = 40"



DISTANCE FROM ANODE - INCHES





its apparent cohesion. It became crumbly and appeared to have some of the properties of a cohesionless soil.

The electrodes required considerable force for their removal. The material around the electrodes seemed to be cemented to the electrodes to such an extent that the soils failed before the bond between the soil and electrode failed. The electrolytic action on the electrodes is shown in figure 9. In places, about half the metal had been eaten away.





CATHODE

A



ANODE

B



ORIGINAL  
CONDITION

C

FIGURE 9





#### EXPERIMENT 4

From figure 7 of experiment 3, it was noted that the soil remained very moist in the area between the electrodes. It was thought that the installation of intermediate electrodes would drain this portion of soil. Four electrodes, A, B, C, and D, similar to those used in experiments 2 and 3 were used. These electrodes were spaced as follows: Electrode A was used as an anode, Electrodes B and C were used as intermediate electrodes and were placed 12" and 21" from the anode respectively and were not connected to the power supply. Electrode D was used as the cathode and was placed 39" from the anode. It was believed that electrode B would act as a cathode for A and as an anode for C and so on.

The starting voltage was 107 and the current was 0.45 amps. The current increased in the usual manner to 0.5 amps in one hour and twenty minutes. It then decreased in a manner characteristic of all the previous experiments. This is shown graphically in figure 10.

Water was driven off electrodes B, C, and D. The water driven off the intermediate electrodes was due to their action as cathodes. Although their spacing was different, nearly identical quantities of water came off electrodes B and C. After 40 hours of treatment, very little



# EXPERIMENT IV

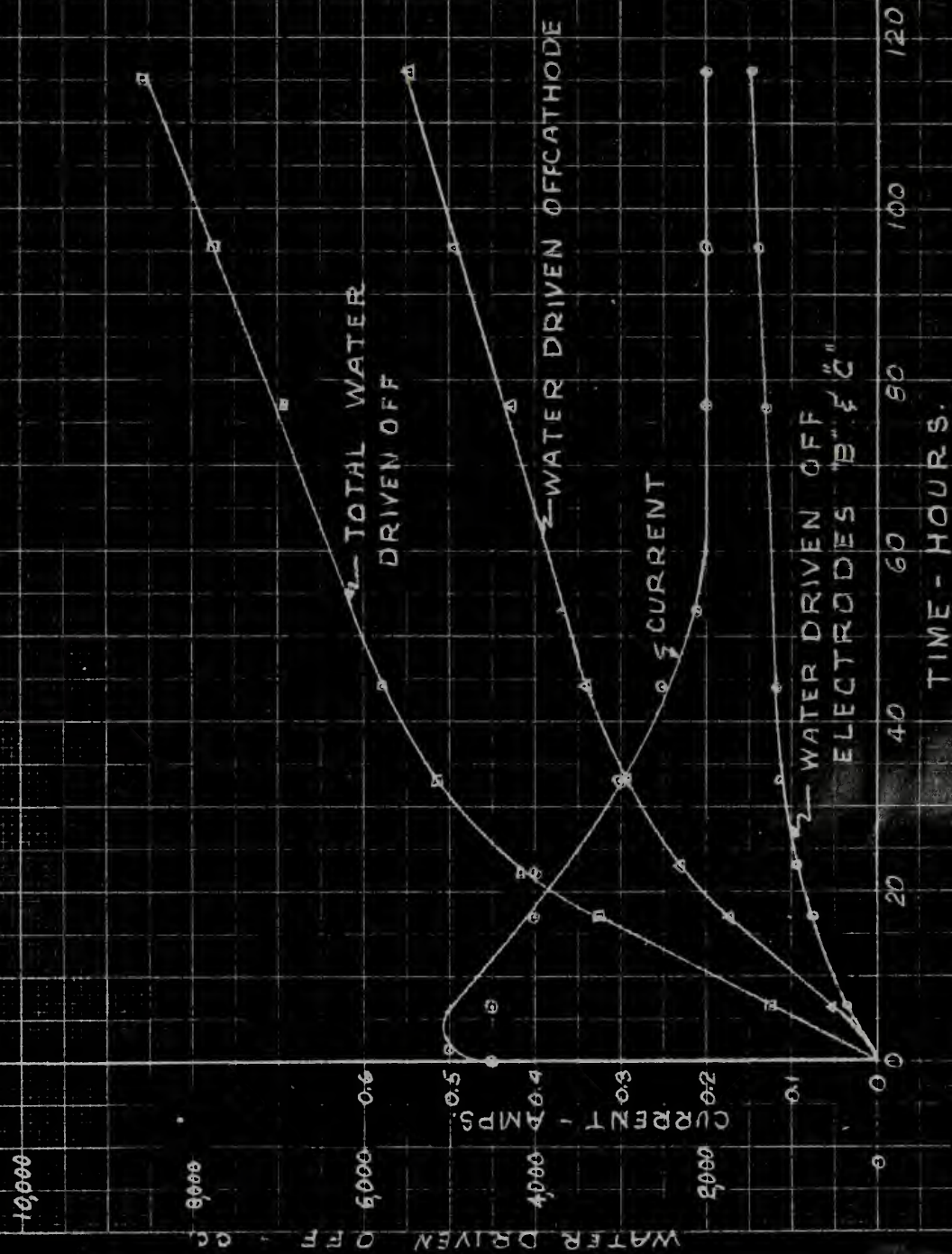


FIGURE 10







water came off electrodes B and C. Comparison of the curves of figure 4 and figure 10 shows the quantity of water coming off the cathode was nearly identical to the quantity coming off the cathode of experiment 3. After 100 hours of treatment, the quantity of water was exactly the same as the amount driven off in experiment 3. The use of the intermediate electrodes had no effect on drainage off the cathode. It had, however, the desired effect of draining the portion of clay in the center and increasing the total amount of water driven off.

From the settlement curves, figure 11, it is evident that the settlement was nearly uniform. The greatest settlement occurred at electrode B. This settlement expressed as a percentage of the original soil depth was 26%.

The current had decreased to 0.2 amps after 116 hours treatment and the current was shut off. The moisture content after treatment is shown in figure 12. The reduction in moisture content reached 47.8% at the anode.

During the removal of the anode, approximately 40 pounds of soil came out with it. The other electrodes



# EXPERIMENT IV

## SETTLEMENT CURVES



FIGURE II







# EXPERIMENT IV

ORIGINAL MC. = 69.2%

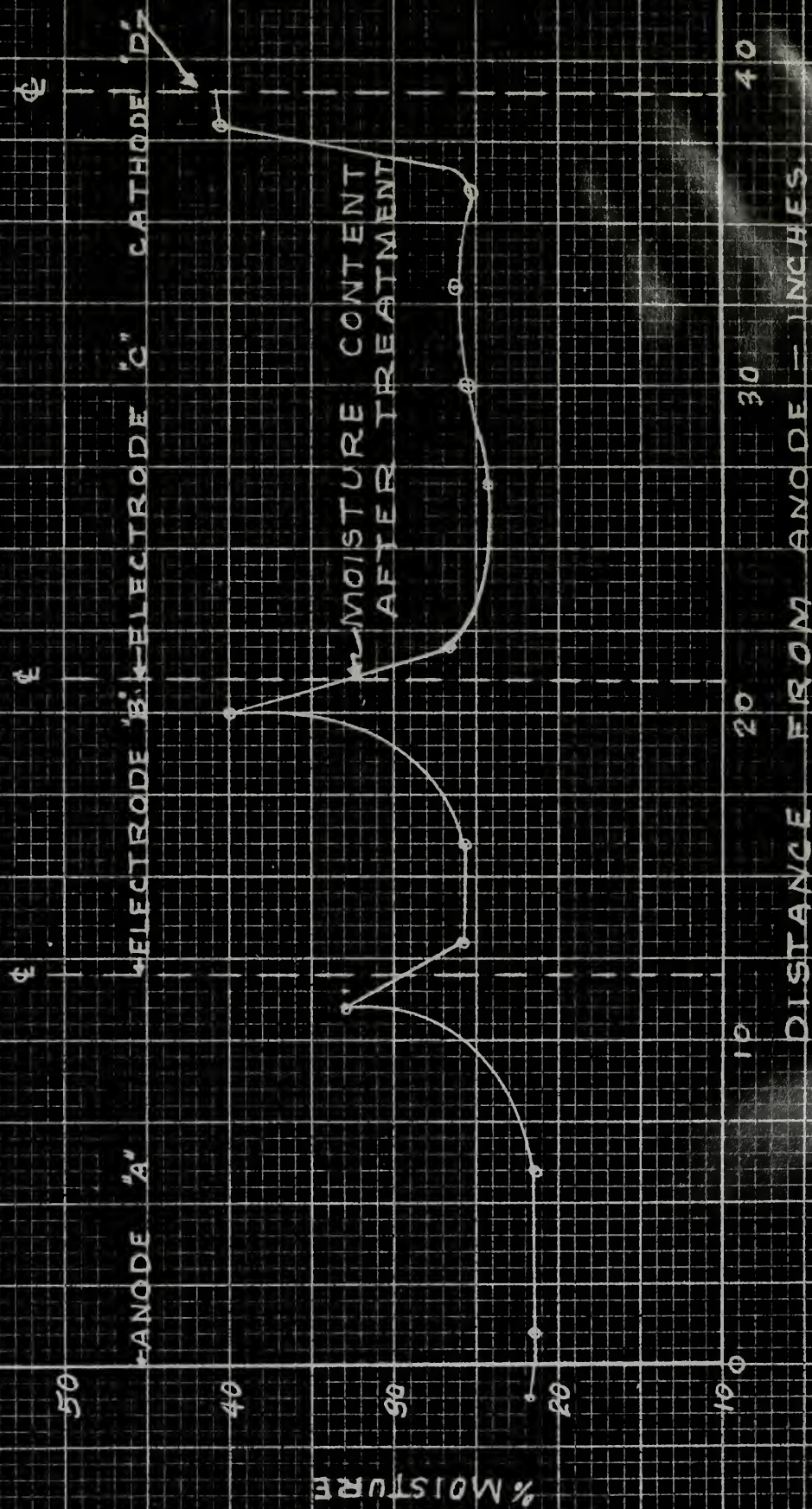


FIGURE 12





were also difficult to remove.

The changes in liquid limit, plastic limit, and plasticity index are shown in figure 13. They follow the general trends shown in the other experiments.

The intermediate electrodes although not connected to the power supply showed definite evidence of cathodic action on the half section facing the anode and anodic action on the side facing the cathode.

A partial submergence test was conducted on cubes of air dried soil. The cube made from the original soil slaked off completely in about twenty minutes. The cubes from the anode and cathode, however, retained much of their original form during several weeks of partial submergence. This test shows that the soil had lost some of its original characteristics. It had lost a great deal of its swelling properties.

Figures 14 and 15 show the set up for experiment 4. The pictures were taken after 16 hours of treatment and show some of the shrinkage cracks which always occurred around the electrodes.





# EXPERIMENT IV

ORIGINAL L.L. = 31.5%  
 " " P.L. = 21.4%  
 " " P.I. = 10.1%

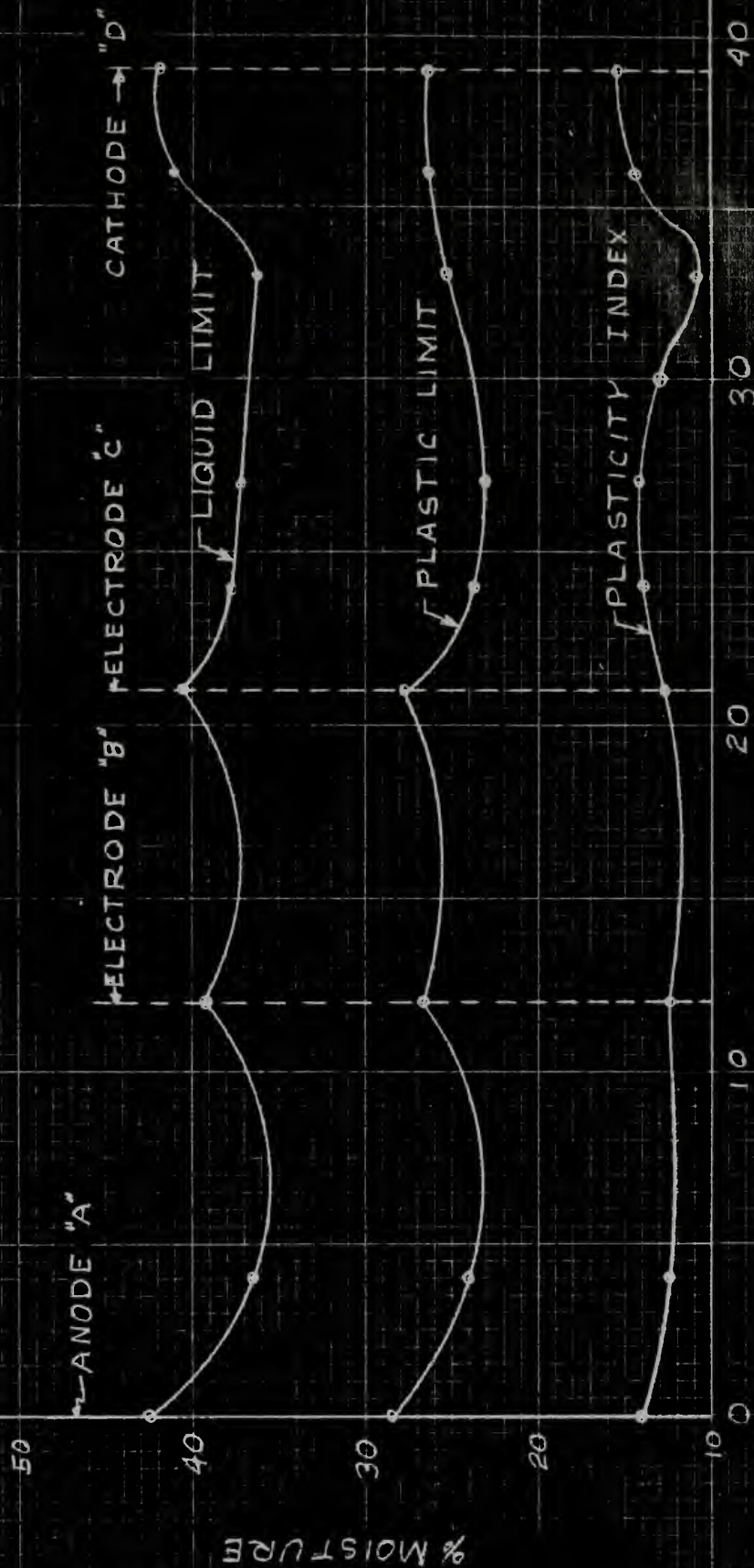


FIGURE 13





Figure 14

Note anodic action on right side of intermediate electrodes,



Figure 15





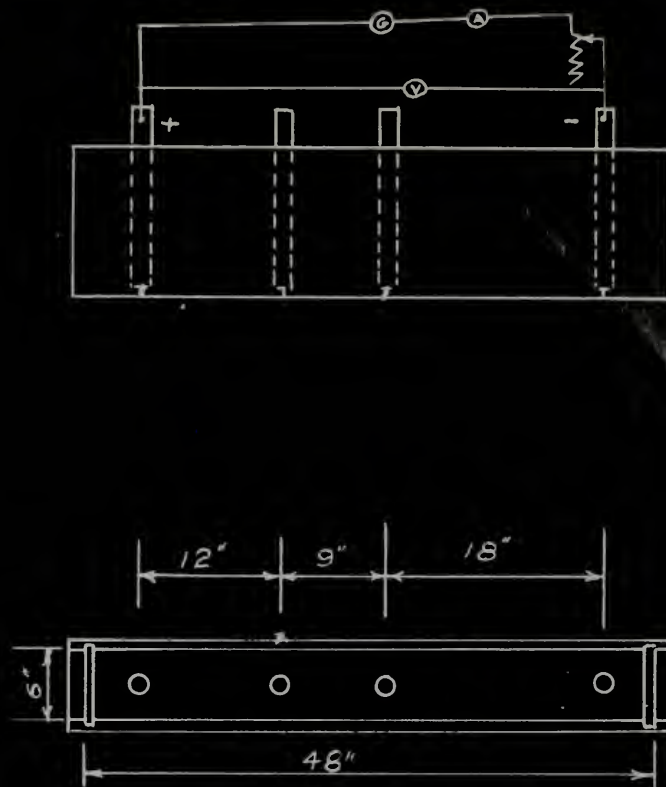


Figure 16

General arrangement of electrodes as used in experiment. Wooden box filled with 1.5 lbs. of clay mod. The electrodes, acting as drainage wells, are perforated aluminum tubes.



## CONCLUSIONS

One of the important conclusions reached by this investigation is that the mechanical properties of some soils can definitely be improved by the electro-chemical treatment of the soil mass. By examination of the liquid limit curves, it is evident that the liquid limit, the plastic limit, and the plasticity index have been considerably increased by this treatment. Since an increase in liquid limit indicates an increase in the shear resistance of the soil at a given moisture content and an increase in plasticity index indicates an increase in cohesion and a change in the shrinkage properties, it can be concluded that the treatment is beneficial in this respect.

One of the reasons for this change in the properties of the soil is a base ion exchange which occurred due to the action of the current.

To explain this, it is believed that the aluminum electrode is eroded by electrolytic action. The aluminum ions migrate into the soil mass by the action of the electric current. These aluminum ions, being trivalent, are more firmly bound to the surfaces of the clay crystals than the divalent or monovalent ions. As a result, the aluminum ions replace the lower valent cations which were adsorbed on the faces of the clay crystals. The replaced





cations, in this case primarily calcium, are carried to the cathode either in the migrating water or by some other method unknown to the author.

When the displaced cations reach the cathode, they unite with OH ions formed by the electrolysis of water. The resulting calcium hydroxide comes off in solution in the water driven off. The liberated hydrogen ions receive electrons from the cathode and go off as a gas. This theory is a possible explanation of what happens at the cathode. The exact action at the electrodes can only be determined by further investigation.

The substitution of aluminum for the cathode instead of using copper had the desired affect. Figure 8 shows that the greatest effect on the liquid limit, the plastic limit, and the plasticity index occurred near the cathode. This indicates that the base ion exchange has been most effective at the cathode.

The settlement data from experiments 3 and 4 show that the soil can be consolidated to a very great extent by this method. As the water is driven out of the soil by electro-osmosis, the soil mass shrinks. This is probably due to a shrinkage of the clay particles with a decrease in adsorbed water and to compressive stresses induced in the soil structure by the action of surface tension. This shrinkage results primarily in a decrease in the volume of the voids. The end results would, therefore, be the same



as the consolidation of a soil mass subject to a compressive stress caused by a surcharge load. It is therefore believed that a layer of wet soft clay could be preconsolidated by the application of electro-osmosis. It is further believed that a consolidation can be accomplished by this method in a few weeks which would be equivalent to many years of consolidation by a surcharge load on a relatively impermeable clay mass.

Settlement calculations could be made to determine the amount of settlement which could be expected to occur and the soil could be preconsolidated to a point which would give an equal voids ratio. If the structure were then built in the soil, there would be little or no settlement.

This theory if true, would allow economic construction to progress in many locations where it has been prohibitive due to excessive settlement or excessive expense. It would also prevent many costly failures of structures which have been erected on this type of soil.

The feasibility of a venture of this type could only be determined in the field and would probably be very costly. It is believed, however, that the end result would be worth the cost.

An examination of the curves in figure 8 shows that







the greatest change in liquid limit, plastic limit, and plasticity index is in the inside six inches between the electrodes. There was, however, a considerable change throughout the entire electrode spacing of 40". It is believed that if it were possible to continue the process longer, the radius of influence would increase with time.

It is interesting to note that the water is driven from the anode to the cathode and water poured into the anode well point is absorbed and driven through the soil mass to the cathode. This leads to a question which should be investigated. Can a solution such as sodium silicate be introduced into the anode and be carried into the soil mass by the current? If this were possible it would probably result in a cementation of the particals in the soil and yield an artificial hardpan.

Experiment 4 showed that the introduction of intermediate electrodes would give similar results to the main electrodes even though not connected to a power supply. It is thought that the action is similar if not identical to the electrolytic action on underground pipes and other conduits or conductors.

Figure 10 as compared with figure 4 shows that the intermediate electrodes had no effect on the action of



the anode and cathode with respect to drainage. They merely added to the efficiency of the process by providing additional drainage and more centers of ionic exchange.

It is the belief of the author that this process has a definite place in the field of soil mechanics and foundation engineering and will be proved economical in many locations where plastic clay or silt is encountered. There are, however, many unknown aspects to the problem and considerable additional research will have to be performed before it can be put to use with predictable results and become unanimously accepted.





## SUGGESTIONS

Clay soil stabilization by electro-osmosis is theoretically sound. Past investigators have shown the method to have considerable merit. A great deal of research will be required, however, before it can become a predictable science.

During this investigation, soil samples have been saved for future investigators to use in their research. Since it is obvious that some change has occurred in the soil, experiments should be carried on to determine exactly what changes have occurred in addition to base ion exchange. The nature of the base exchange should also be determined by chemical methods.

The soil immediately around the cathode changed so much in physical appearance that a possible change or breakdown in the crystalline structure of the clay has occurred. It will be necessary to analyze this clay by differential thermal analysis, X-ray analysis and microscopic examination to determine the exact nature of this change.

The effect of time on the ion exchange should be determined. It is necessary to find out if this base exchange is a fractional process. That is, are all types of cations driven off simultaneously or will different cations be driven off by themselves? To

The first of these is the fact that the  
 present system of taxation is not  
 based on the principle of equity. It is  
 based on the principle of expediency. It is  
 based on the principle of expediency. It is  
 based on the principle of expediency.

The second of these is the fact that the  
 present system of taxation is not  
 based on the principle of equity. It is  
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determine this, the water drained off can be analysed chemically at intervals over a long period of time. Water samples have been saved from experiment 4 for part of this investigation.

The possibility of driving some solution into the soil which will cause cementation should be investigated by pouring the solution into the anode well point so it can be absorbed. It is possible that an artificial hardpan could be formed in this manner.

Experiments should be run in the field to study the effect of field conditions on the process. An economic study could be made under field conditions could be made at this time.

An investigation of the increased holding power of piles in soil subjected to this treatment should be made. The electrodes were very firmly held in the clay after treatment. It would seem, therefore, that piles used as electrodes should exhibit remarkable holding power.

The use of different metals as electrodes should be tried to determine their effect on soil properties and the type of ions driven off. This should give information as to the reversibility of the process





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APPENDIX





EXPERIMENT 1

## Data sheet

Time hours	Amps	Amp hours	Volts	Water drained off
0.00	1.0	0.0	107	0
0.75	1.1	0.79	107	--
1.17	1.2	1.27	110	100 cc
6.00	0.4	5.13	113	493 cc
30.00	0.3	13.88	106	1213 cc



# EXPERIMENT 1

Moisture content data:

No.	Dist. from surface	Net weight	Dry weight	Cont. weight	Water	Dry soil	moist.	reduction
1	**	34.503	29.047	19.367	5.256	9.680	54.3	----
2	1"	29.991	27.666	19.416	2.328	8.250	38.2	26.1
3	11"	25.780	24.084	18.489	1.696	5.593	30.3	24.0
4	6"	30.303	27.779	19.293	2.524	8.486	29.8	24.8

\*\* Moisture prior to treatment.





# EXPERIMENT 1

Liquid and plastic limits after treatment.

No.	Dist. from anode	No. blows	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.
9	0"	17	28.921	26.061	19.457	2.860	6.604	43.3
10	0"	34	25.455	23.825	19.819	1.630	4.006	40.6
11	0"	24	27.231	30.464	20.014	3.833	7.318	41.5
5	0"	P.L.	18.071	17.035	12.797	1.036	4.238	24.4
7	12"	15	16.977	15.067	11.739	1.910	3.382	57.3
8	12"	28	20.021	17.590	12.169	2.431	5.421	44.9
12	12"	33	32.989	29.342	20.986	3.647	8.356	43.5
6	12"	P.L.	18.477	17.202	12.511	1.275	4.691	27.1
1	Original soil	13	27.559	25.506	19.368	2.053	6.138	33.4
2	"	46	24.553	23.202	18.717	1.351	4.485	30.1
3	"	25	31.052	28.232	19.183	2.820	9.049	31.2
4	"	P.L.	26.787	25.463	19.293	1.324	6.170	21.4
4	6"	P.L.	24.724	23.623	19.293	1.101	4.330	25.4





EXPERIMENT I

LIQUID LIMITS	
ANODE	41.5%
CATHODE	47.6%
ORIGINAL SOIL	31.4%



LIQUID LIMIT  
AT 25 BLOWS.

NUMBER OF BLOWS





EXPERIMENT 11

## Data sheet

Time hours	Amps	Amp hours	Volts	Water off cathode	cumulated water
0.00	1.2	0.0	110	0	0
0.33	1.2	0.4	110	110 cc.	110 cc.
00.92	1.2	1.1	110	143 cc.	253 cc.
1.33	1.2	1.6	110	120 cc.	373 cc.
1.63	1.25	1.97	107	74 cc.	447 cc.
2.00	1.25	2.41	110	113 cc.	560 cc.
18.25	0.4	15.81	106	1830 cc.	2390 cc.
20.25	0.4	16.61	106	158 cc.	2548 cc.
46.25	0.2	24.21	109	285 cc.	2833 cc.



# EXPERIMENT 11

Moisture content data:

No.	Dist. from anode	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.	% reduction
13	**	34.586	29.493	18.927	5.093	10.566	48.5	----
4	0"	29.026	27.411	19.293	1.795	8.118	22.1	26.4
9	6"	29.910	27.788	19.695	2.122	8.093	26.2	22.3
1	12"	32.006	29.091	19.368	2.9155	9.723	30.0	18.5

\*\* Moisture prior to treatment.





EXPERIMENT LL

Liquid limit and plastic limit data.

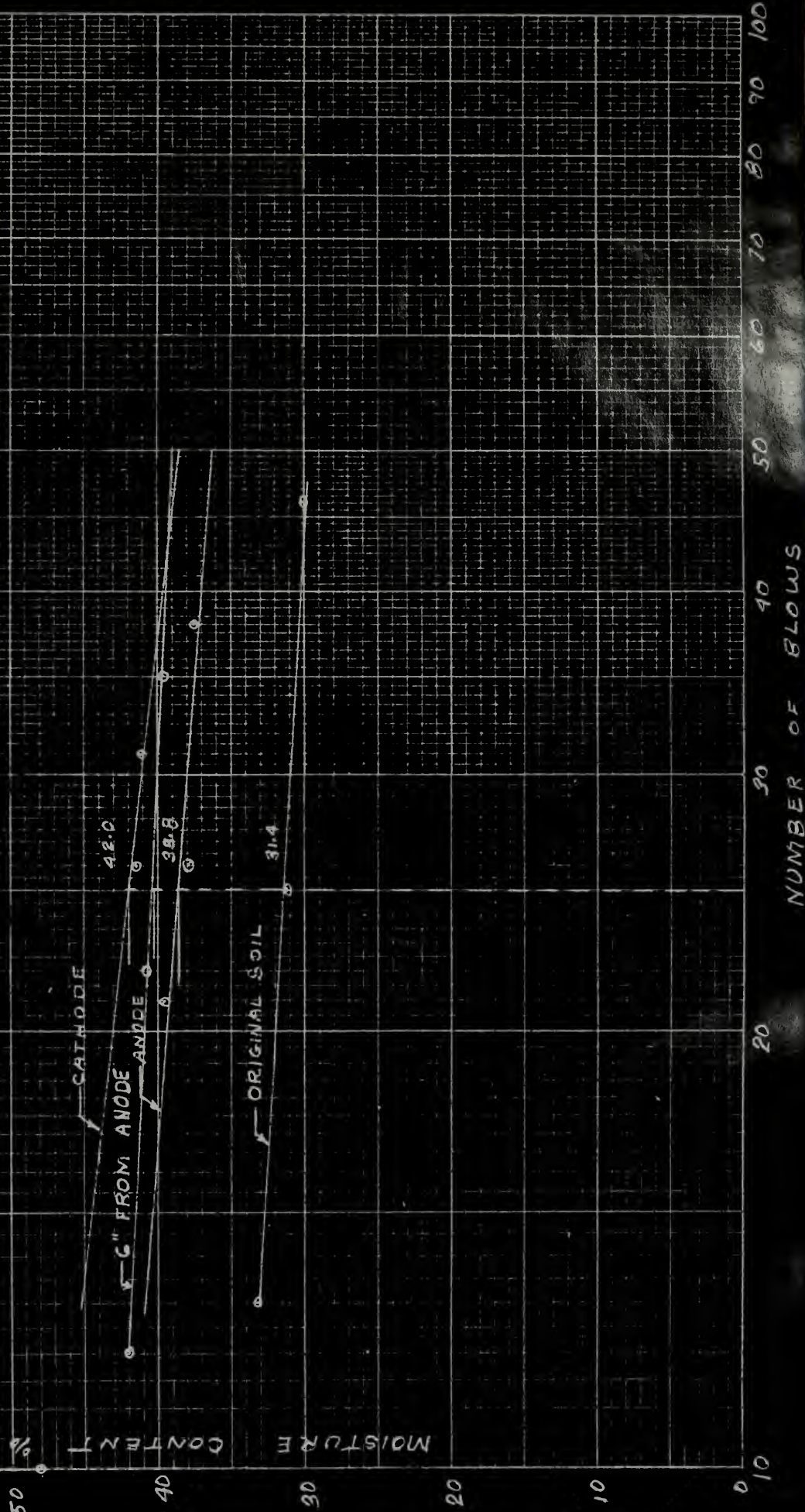
No.	Dist. from anode	No. blows	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.
6	0"	38	19.781	17.711	12.186	2.070	5.525	37.5
5	0"	21	20.852	18.412	12.266	2.440	6.147	39.7
7	0"	26	19.879	17.612	11.564	2.279	6.036	37.9
8	0"	P.L.	18.767	17.612	12.801	1.155	4.811	24.0
10	Cathode	31	28.374	25.996	20.223	2.378	5.773	41.1
11	"	10	29.183	26.186	19.980	2.996	6.206	48.1
13	"	26	31.382	28.177	20.431	3.205	7.745	41.5
9	"	P.L.	25.524	24.278	19.692	1.246	4.586	27.1
12	6"	12	28.859	26.154	19.692	2.705	6.462	42.0
13	6"	35	30.106	27.359	20.431	2.747	6.928	34.7
11	6"	22	30.076	27.148	19.980	2.928	7.168	40.8
9	6"	P.L.	25.016	23.815	18.929	1.201	4.886	24.7



# EXPERIMENT II

## LIQUID LIMITS

ANODE	38.8
CATHODE	42.0
ORIGINAL SOIL	31.4
6" FROM ANODE	40.3









EXPERIMENT 111

## Data sheet

Time hours	Amps	Amp hours	Volts	cc water	cumulative water	Remarks
0.0	0.35	0	105	0	0	
1.83	0.40	0.69	107	180	180	
2.83	0.41	1.09	108	170	350	
3.83	0.40	1.50	"	85	435	100 cc. sample taken.
4.83	"	1.90	"	115	550	
5.83	"	2.30	"	122	672	
6.83	"	2.70	"	142	814	
10.25	"	4.07	"	410	1224	Cracking around both electrodes.
15.25	"	6.07	"	496	1720	Marked cracking.
27.25	"	10.87	111	896	2616	Cracks tamped in.
31.17	"	12.47	"	320	2936	100 cc. sample taken.
52.25	0.3	19.82	"	1054	3990	Sample taken.
71.50	0.25	25.12	112	750	4740	
96.0	0.2	30.62	115	500	5240	
124.75	0.1	34.89	110	345	5585	



# EXPERIMENT 111

Moisture content after treatment.

No.	Dist. from anode	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.	% reduction
12	0"	28.741	27.119	18.929	1.622	8.190	19.8	44.7
11	1.5"	24.719	23.684	19.980	1.035	3.704	27.9	36.6
10	3"	29.177	27.594	20.223	1.583	7.371	21.5	43.0
8	6"	19.013	17.818	12.891	1.195	5.017	23.8	40.7
13	9"	36.168	32.782	20.431	3.368	12.351	27.3	37.2
7	12"	18.220	16.656	11.564	1.564	5.092	30.7	33.8
6	15"	17.321	15.806	12.186	1.515	3.620	41.8	22.7
1	18"	32.038	28.340	19.368	3.698	8.972	41.2	23.3
5	21"	17.610	15.944	12.266	1.666	3.678	45.3	19.2
17	24"	62.371	55.155	39.397	7.216	15.758	45.7	18.8
16	27"	62.712	58.457	45.119	4.255	13.338	31.9	32.6
14	30"	71.581	66.669	48.308	4.912	18.361	26.8	37.7
2	36"	24.985	23.618	18.717	1.367	6.901	19.8	44.7
9	36"	25.549	24.174	19.692	1.375	4.482	30.7	33.8
4	38.5"	28.603	25.905	19.293	2.698	6.612	40.6	23.9
3	40"	29.452	26.557	19.184	2.895	7.373	39.2	25.3
***		30.207	25.929	19.293	4.278	6.636	64.5	

---

\*\*\* - Moisture prior to treatment.





EXPERIMENT 111

Settlement data.

Time hours	Settlement at cathode	Settlement at anode	Settlement between electrodes
6.00	0.625"	0.375"	0.25"
27.0	1.00"	0.875"	0.375"
52.0	1.50"	1.250"	0.75"
96.0	1.5"	1.250"	1.00"
125.0	1.50"	1.375"	1.50"

Note: The greatest settlement occurred at a distance of one foot from the anode and this settlement was 1.75 inches.



EXPERIMENT 111

Liquid Limit data:

No.	Dist. from anode	No. blows	Cont.+ wet weight	Cont.+ dry weight	Cont. weight	Water	Dry soil	% M.C.	
11	0"	20	25.846	24.160	19.980	1.686	4.180	40.0	
9	0"	32	26.887	24.907	19.692	1.980	5.215	38.0	
12	0"	13	26.828	24.471	18.929	2.357	5.542	42.6	
10	0"	P.L.	29.566	27.799	20.223	1.767	7.576	23.3	
2	6"	38	25.598	23.801	18.717	1.797	5.084	35.3	
4	6"	31	25.558	23.916	19.293	1.642	4.623	35.6	
10	6"	24	26.513	24.819	20.223	1.694	4.596	36.9	
3	6"	16	27.055	24.875	19.184	2.180	5.691	38.3	
7	6"	P.L.	18.208	16.997	11.564	1.211	5.433	22.3	
5	12"	23	18.462	16.816	12.266	1.646	4.550	36.2	
6	12"	20	19.212	17.292	12.186	1.920	5.106	37.6	
8	12"	29	18.819	17.231	12.801	1.588	4.430	35.8	
16	12"	35	57.161	54.086	45.119	3.075	8.967	34.3	
14	12"	P.L.	56.510	54.973	48.308	1.537	6.665	23.05	
12	24"	11	26.297	24.201	18.929	2.096	5.272	39.7	
1	24"	15	27.012	24.918	19.368	2.094	5.550	37.7	
4	24"	25	28.548	26.421	20.431	2.127	5.990	35.5	
3	24"	37	28.627	26.265	19.184	2.362	7.081	33.4	
9	24"	P.L.	29.030	27.347	19.692	1.683	7.655	22.0	





EXPERIMENT 111

Liquid Limit data continued:

No.	Dist. from anode	No. blows	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.
13	30"	15	28.796	26.553	20.431	2.243	6.122	36.7
12	30"	39	25.155	23.587	18.929	1.568	4.658	33.6
1	30"	30	26.217	24.457	19.368	1.760	5.089	34.6
9	30"	20	26.218	24.515	19.692	1.703	4.823	35.4
11	30"	P.L.	25.613	24.566	19.980	1.047	4.586	22.85
6	36"	36	16.071	15.062	12.186	1.009	2.876	35.1
8	36"	27	18.377	16.889	12.801	1.488	4.088	36.4
5	36"	10	16.991	15.654	12.266	1.337	3.388	39.5
16	36"	25	57.384	54.131	45.119	3.253	9.012	36.1
14	36"	P.L.	62.727	60.049	48.308	2.678	11.741	22.8
2	Cathode	38	25.181	23.187	18.717	1.994	4.470	44.6
4	"	28	25.162	23.278	19.293	1.884	3.985	47.2
1	"	17	28.675	25.544	19.368	3.131	6.176	50.7
13	"	P.L.	28.189	26.421	20.431	1.768	5.990	29.5

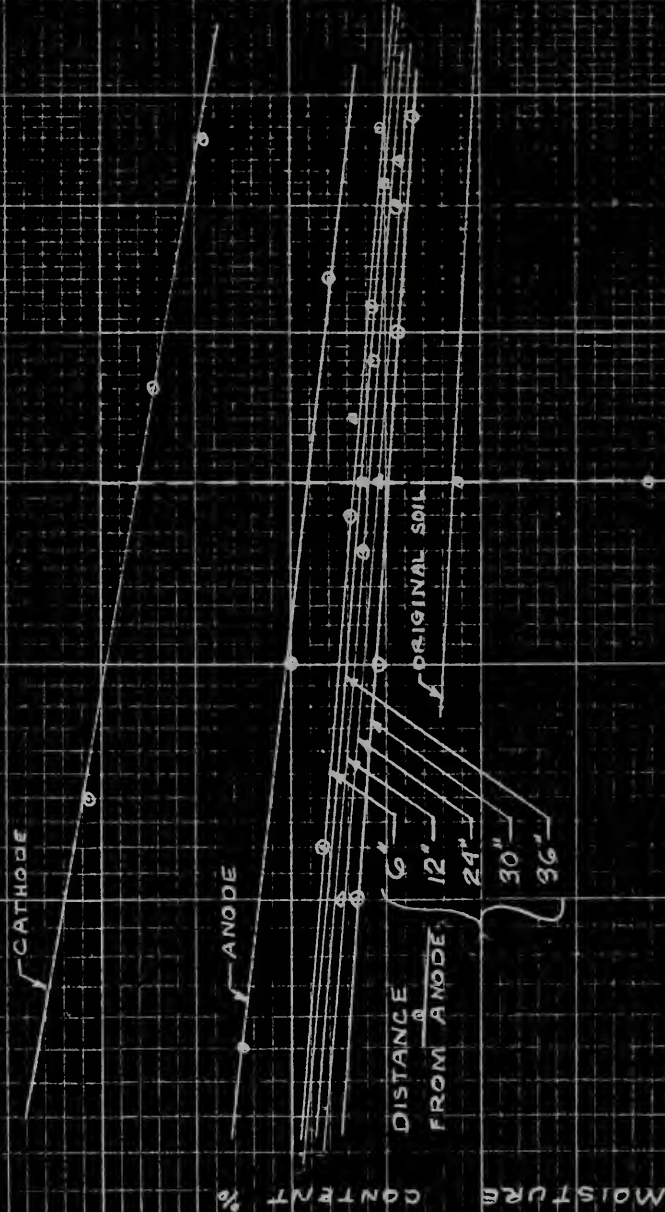




# EXPERIMENT III

## LIQUID LIMITS

ANODE	39.1 %
CATHODE	48.0 %
6" FROM ANODE	36.7 %
12"	35.9 %
24"	35.4 %
30"	34.8 %
36"	36.4 %
ORIGINAL SOIL	31.4 %







# EXPERIMENT 1V

## Data sheet

Time hours	V A -D	V A-B	V B-C	V C-D	I	Water off B	Water off C	Water off D	Water off total
0.0	107	35	21	51	.45	0	0	0	0
1.3	108	35	21.5	51.5	.5	64	68	64	196
6.4	106	35	21	50	.45	340	400	520	1260
17.0	110	39	21	50	.40	750	780	1730	3260
23.0	109	38	20	50	.40	922	948	2300	4170
33.0	109	46	18	45	.30	1102	1108	2910	5120
44.0	116	56	17	42	.25	1187	1193	3400	5780
77.0	110	65	12	32	.20	1282	1368	4290	6940
95.5	109	59	12	37	.20	1362	1438	4950	7750
116.0	110	49	11	49	.20	1632	1448	5490	8570

Note: One thousand cc. of water was added to the anode after seventy seven hours and at ninety five hours. The water added was almost immediately absorbed into the soil with a resultant decrease in the electrical resistance near the anode.



EXPERIMENT 1V

Moisture content after treatment.

No.	Dist. from anode	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% moist.	% reduction
10	-1"	32.723	30.491	20.224	2.232	10.267	21.7	47.5
11	1"	27.294	26.002	19.980	1.292	6.022	21.4	47.8
4	6"	25.189	24.151	19.293	1.038	4.858	21.4	47.8
1	11"	30.130	27.464	19.368	2.666	8.096	33.0	36.2
3	13"	29.215	27.158	19.184	2.057	7.974	25.8	43.4
2	16.5"	34.227	31.061	18.719	3.164	12.342	25.7	43.5
12	20"	26.773	24.545	18.929	2.248	5.616	40.0	29.2
6	22"	34.667	31.515	19.692	3.152	11.823	26.7	42.5
7	27"	20.192	18.505	11.564	1.687	6.961	24.2	45.0
17	30"	57.396	53.705	39.397	3.691	14.308	25.8	43.4
5	33"	18.719	17.127	11.097	1.592	6.030	26.4	42.8
6	36"	20.380	18.724	12.168	1.656	6.556	25.2	44.0
8	38"	21.754	19.160	12.801	2.594	6.359	40.7	28.5
***		32.118	27.300	20.224	4.818	7.076	69.2	---

\*\*\* - Moisture content prior to treatment.





EXPERIMENT 1 V

Settlement data.

Time hours	Distance from anode- Settlement in inches							
	0"	6"	12"	18"	24"	30"	36"	39"
1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6.75	0.25	0.375	0.375	0.25	0.25	0.25	0.25	0.25
17.4	1.25	1.0	1.0	0.75	0.75	0.625	0.875	0.75
24.0	1.375	1.125	1.25	1.0	1.25	0.75	1.0	1.125
33.0	1.50	1.375	1.375	1.0	1.25	0.875	1.125	1.125
45.0	1.75	1.75	1.75	1.75	1.50	1.125	1.50	1.325
77.0	2.125	2.25	2.50	2.125	2.125	1.75	1.75	1.875
95.5	2.125	2.25	2.50	2.125	2.25	1.875	1.75	1.875
116.0	2.125	2.25	2.50	2.125	2.25	1.875	1.875	1.875



# EXPERIMENT 1V

Liquid limit and plastic limit data.

No.	Dist. from anode	No. blows	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% Moist.
1	24"	17	26.175	24.262	19.368	1.913	4.894	39.1
12		31	24.928	23.314	18.929	1.614	4.385	36.8
2		23	25.184	23.411	18.719	1.773	4.692	37.9
4		20	25.056	23.436	19.293	1.620	4.143	39.0
11		P.L.	24.569	23.687	19.980	0.882	3.707	23.8
4	27"	14	23.700	22.466	19.293	1.234	3.173	39.0
12		29	25.796	23.937	18.929	1.614	4.385	36.8
2		35.	24.706	23.312	19.368	1.394	3.944	35.4
9		P.L.	25.125	24.110	19.692	1.015	4.418	23.0
25	33"	12	24.663	23.242	19.585	1.421	3.657	38.9
2		26	24.563	23.015	18.719	1.548	4.296	36.1
4		37	25.067	23.590	19.293	1.477	4.297	34.4
26		P.L.	17.826	16.810	12.848	1.016	3.962	25.6
9	36"	33	24.318	23.013	19.692	1.305	3.321	39.3
10		26	26.083	24.383	20.223	1.700	4.160	40.8
3		22	25.079	23.336	19.184	1.743	4.152	42.0
7		13	17.036	15.352	11.562	1.684	3.788	44.4
5		P.L.	17.925	16.738	12.268	1.187	4.470	26.5
10	cathode	10	27.071	24.818	20.223	2.253	4.595	49.0
11	"	19	27.700	25.350	19.980	2.350	5.370	43.8
2	"	26	25.491	23.532	18.719	1.959	4.813	40.6
3	"	P.L.	22.685	21.952	19.184	0.733	2.768	26.5





# EXPERIMENT 1V

Liquid limit and plastic limit data.

No.	Dist. from anode	No. blows	Wet weight	Dry weight	Cont. weight	Water	Dry soil	% Moist.
6	0"	24	16.461	15.176	12.186	1.285	2.990	43.0
8	0"	34	16.964	15.692	12.801	1.272	2.891	41.4
11	0"	14	25.318	23.708	19.980	1.610	3.728	44.0
5	0"	28	16.927	15.556	12.268	1.371	3.288	41.8
7	0"	P.L.	15.020	14.253	11.564	0.767	2.689	28.5
9	4"	11	25.343	23.736	19.692	1.607	4.044	39.8
1		25	24.351	23.040	19.368	1.311	3.672	35.7
10		35	24.804	23.494	20.223	1.310	3.271	35.0
12		23	25.089	23.419	18.929	1.670	4.490	37.2
3		P.L.	26.572	25.140	19.184	1.432	5.956	24.0
27	12"	11	17.381	15.955	12.765	1.426	3.190	44.7
28		24	17.373	15.874	11.993	1.499	3.881	38.6
30		35	18.795	17.028	12.342	1.767	4.686	37.6
31		P.L.	17.295	16.343	12.900	0.952	3.443	26.7
20	21"	24	24.302	22.806	19.137	1.496	3.669	40.8
21		18	26.300	24.576	20.551	1.724	4.025	42.8
22		13	24.327	22.620	18.700	1.707	3.920	43.5
23		36	26.710	24.610	19.183	2.100	5.427	38.7
24		P.L.	25.510	24.250	19.747	1.260	4.503	27.9



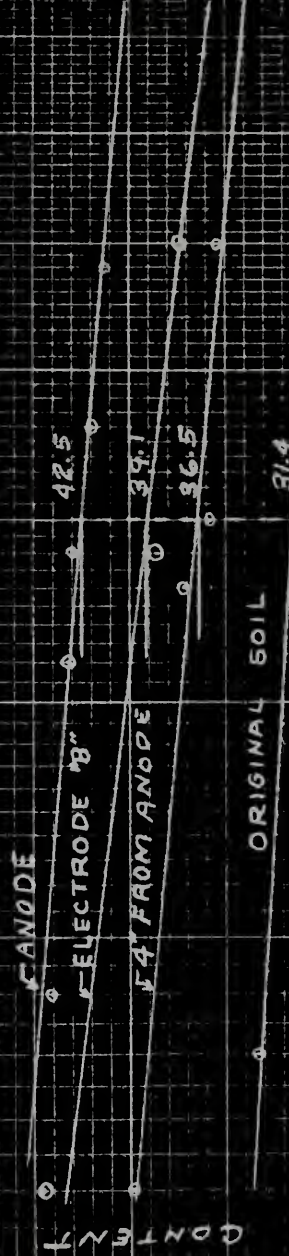


# EXPERIMENT IV

## LIQUID LIMITS

ANODE	42.5
4" FROM ANODE	36.5
ELECTRODE B	39.1
ORIGINAL SOIL	31.4

MOISTURE CONTENT



NUMBER OF BLOWS

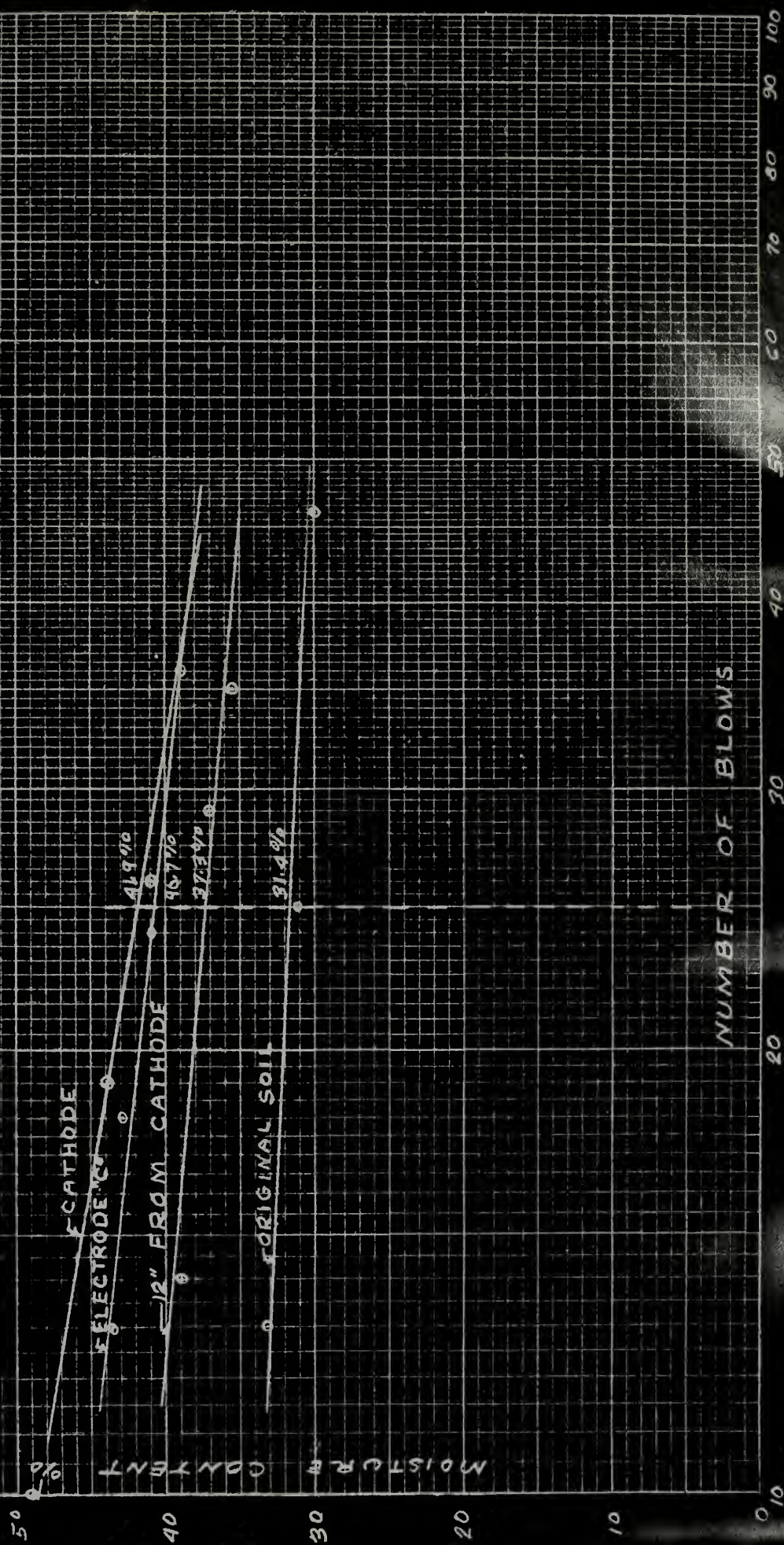




# EXPERIMENT IV

## LIQUID LIMITS

CATHODE 41.9"  
 12" FROM CATHODE 37.9"  
 ELECTRODE "C" 40.7"  
 ORIGINAL SOIL 31.4"



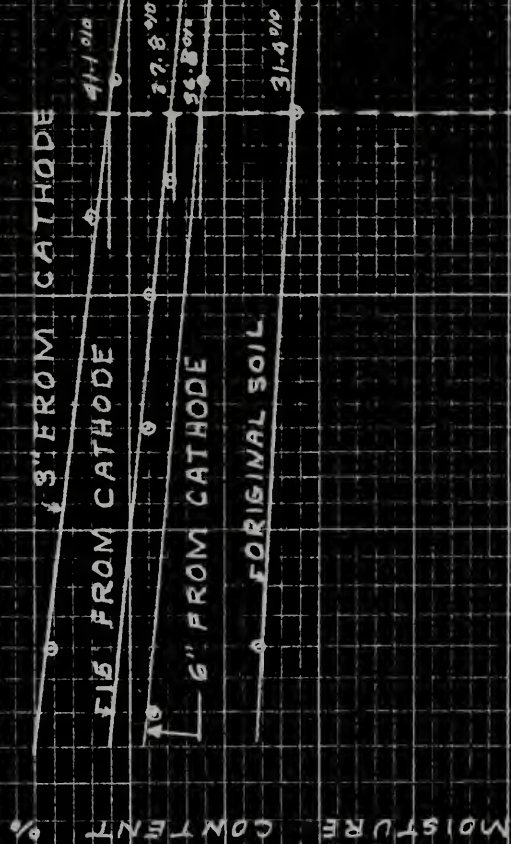




# EXPERIMENT IV

## LIQUID LIMITS

3" FROM CATHODE	41.1
6" FROM CATHODE	36.3 %
15" FROM CATHODE	37.8 %
ORIGINAL SOIL	31.9 %



NUMBER OF BLOWS











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